

Final Report

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**Evaluation of Rapid Setting Cement-Based
Materials for Patching and Repair**

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CHAPTER 1: INTRODUCTION, OBJECTIVES, AND APPROACH

1.1 Introduction

The efficient repair and replacement of concrete pavements often requires a rapid setting material that can be placed, cured, and opened to traffic in a relatively short period of time. Frequently, temporary repairs are made using materials that are later found to be incompatible with the existing pavement, structures, and environment. This practice causes these materials to fail prematurely, frequently requiring re-repair. Recently, several high early-strength cement repair material compositions (both generic and proprietary) have been developed. However, these rapid setting materials are extremely susceptible to environmental conditions, poor bond, and early-age cracking and deterioration. Research is needed to determine which rapid setting repair materials demonstrate the best behavior with rapid strength gain, low potential for cracking, and excellent durability.

While Section 901 of the current INDOT specification describes how repair materials are to be tested, this specification focuses primarily on insuring that the materials achieve the minimum strength and bond properties. Frequently, repair materials that have sufficient strength are found to fail prematurely since they may have other properties, like rapid development of stiffness and high shrinkage, which can result in an incompatibility with the surrounding materials that can ultimately lead to cracking. Furthermore, the use of a single repair material for every application is not feasible. For example, concrete pavement panel stitching materials are used in a relatively low volume so the cost of the materials themselves may be a relatively small part of the overall job cost, however full depth repairs or white topping are used large volumes and the materials cost can be a significant portion of the overall cost of the system. In addition, one repair material may not be appropriate for every application and the materials must be selected based on the anticipated useful life that is required from a given repair.

1.2 Research Objectives

The objective of this research is to evaluate the performance of rapid setting cement-based repair materials that will be used in applications ranging from the patching of concrete pavements and bridge decks to the paving of critical intersections and pavements that can not be closed for extended period of time. This project is intended to assist INDOT in development of tools for the assessment of various repair materials for different environmental conditions and intended application. Consideration will be given to parameters such as rate of strength (stiffness) gain, volume stability, bond, and the environment the material can be placed in.

1.3 Research Approach

The goal of this project was to provide the INDOT with information to fully assess and compare the performance of various rapid setting repair materials. This research investigated the influence of surface preparation conditions on the ultimate performance of the repair material. The specific tasks considered in this proposal are discussed in more details in the following sections.

1.3.1 Task 1: Literature Review and Material Collection

In the first phase of the project, a review of literature was conducted pertaining to the use of cement-based repair materials. The researchers focused on developing a list of materials that are being used in Indiana (from the approved list), materials that have been previously used, and materials that may be used elsewhere. Specifically researchers noted the pros and cons of using these materials with respect to their workability, strength development, volume stability, and propensity for premature cracking. This data was gathered from a variety of resources ranging from the INDOT approved source list and a conventional literature review. Surveys were prepared and sent to each district to determine which repair materials and procedures were currently being used for concrete repairs. The final step of Task 1 was to request, from state suppliers, representative samples of repair materials to enable conducting the necessary experimental procedure to assess the material properties described below.

1.3.2 Task 2: Rate of Mechanical Property Development

Task 2 focused primarily on performing a materials characterization to determine the rate and the magnitude of material property development. Preliminary research was conducted using maturity-based concepts to determine the maturity at which a material begins to gain strength as well as the rate of strength development. Understanding the rate of property development is important since if the strength gain starts too quickly (i.e., very rapid setting), there is not enough time to allow for the proper placement of the material. On the contrary, if the reaction rates and the strength gain is too slow, the mixture will not gain sufficient strength which ultimately causes a delay in the opening of the structure. Specifically testing will be performed to determine compressive strength, elastic modulus and flexural strength that incorporate maturity concepts.

1.3.3 Task 3: Volume Stability and Cracking Potential

It is widely believed that concrete made using a low water-to-cement ratio (w/c) typically exhibits lower drying shrinkage. For this reason many people believe that early-age cracking caused by shrinkage would not be a problem in repair materials since these materials typically use a low water-to-cement ratio (w/c) to achieve a high strength. However, it has recently been observed that higher strength (especially high early strength) concretes are more susceptible to cracking. This has been attributed to four-main factors: increased autogenous shrinkage, increased stiffness, decreased creep, and increased brittleness. These factors can be exasperated in rapid setting repair materials due to the paste volume and rapid rate of material property development. As a result of the rapid development of elastic modulus and decrease in creep compliance, the ability for repair materials to redistribute stresses may be altered thereby increasing the potential for cracking.

A substantial amount of autogenous shrinkage can occur in materials with a low water to cement ratio especially during the first 24 hours of material development. This can be significant in rapid setting repair materials. To accurately measure early shrinkage and expansion movements, researchers will use a special system with non contact laser probes to assess volumetric changes while the specimen is still in the forms. These results will be added to the more typical ASTM C-157 shrinkage results.

Since early-age cracking is prevalent in cement-based materials, restrained ring tests will be used in which an annulus of the repair material is cast around a rigid steel ring. During the test, the ring of repair material wants to shrink and get smaller, but the steel ring prevents its movements, resulting in the development of circumferential stresses that can lead to cracking. The maximum tensile stress that develops in the repair material will be computed which enables assessing the cracking potential for cases where visible cracking may not be observed.

1.3.4 Task 4: Bond with Various Surfaces

Achieving adequate bond between repair materials and the existing concrete substructure is a key component for any repair material. This bond information is needed to insure adequate stress transfer during loading, expansion, and contraction. Various techniques are used to prepare the subsurface that may result in different degrees of mechanical and chemical bond between the subsurface and the repair patch. Currently INDOT utilizes the slant shear test as an acceptance method to evaluate the bond quality. This test provides a reproducible value for comparison purposes, however the applicability of the results depends on the actual subsurface preparation method used in the field. This work will focus on distinguishing between shear and tensile strength of the bond. Specimen surfaces will be prepared with different roughnesses to better quantify the contribution of the bond as either a chemical or physical process for the different materials. By distinguishing between the two aspects of this bond (shear and tensile) it is hoped that insight will be able to be gained for use in assessing not only the initial bond strength.

CHAPTER 2: LITERATURE REVIEW

2.1: Introduction

Rapid repair of pavements or bridges is frequently necessary so that there is minimal disruption to the traveling public. This document investigates the mechanical properties of several different ‘rapid’ repair materials. The term ‘rapid’ is used in this context to describe materials that gain strength at a rate such that a facility can be reopened to service approximately 4 to 6 hours after the repair materials are placed. While the mechanical properties will be investigated thoroughly in chapter 3, the repair process is a multi step process and as such many factors will govern the success of a repair. The primary objective of this chapter is to provide the reader with an overview of the factors that should be considered before a repair material is selected for a specific repair application. This chapter will illustrate which properties of a repair material may be the most desirable for long-term performance.

2.2: The Repair Process

There are several factors that dictate the success of a repair project. These include the design of the repair, the demolition of the existing damaged concrete, the surface preparation of the substrate to receive the repair material, the selection of the repair material, the quality of the material placement and finishing, and the inspection of the work. Several questions need to be asked when a damaged facility is analyzed before a repair material and strategy can be selected. Figure 2.1 provides an example of some of the questions that should be considered in the analysis of a damaged facility while a

repair strategy is being developed. It should be noted that the engineer designing the needs to pay special attention to the fact that their design needs to be compatible with the existing structure, exposure conditions, and user expectations of the facility. In addition, the question must be raised as to how long a facility may be ‘closed’ while the repair is preformed.

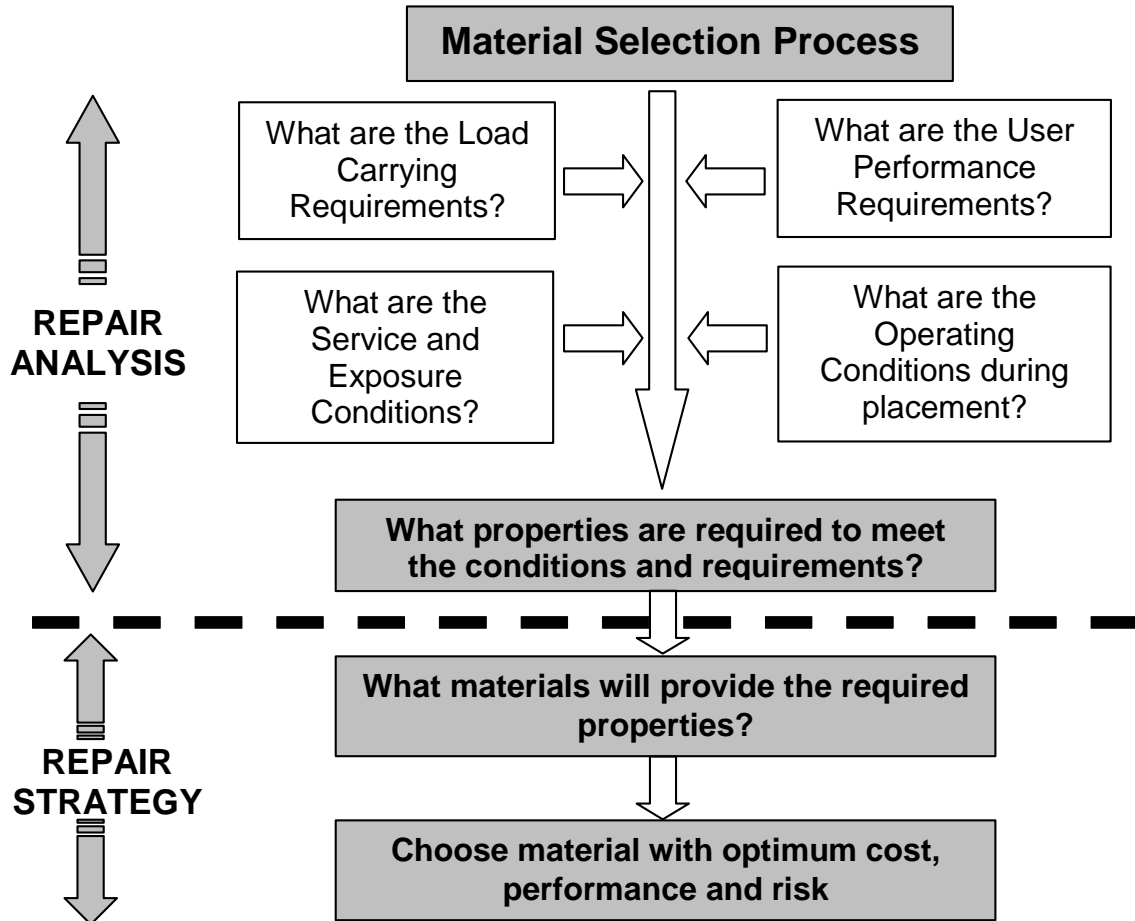


Figure 2.1: A Flowchart Illustrating Questions To Consider Before Selecting a Repair Material (after Emmons, 1993)

This report is written focusing on the repair of concrete pavements and bridge decks that exhibit surface spalling although the findings of this report may be applicable to other

repair situations. These repair materials will frequently be expected to be placed in a relatively harsh environment where freezing and thawing, chloride exposure, and drying and wetting take place. The materials are generally placed while the facility remains in use by closing the lane in which the repair will be performed and diverting traffic into the neighboring lane. It is crucial in many locations that lane closures do not last for an extended period of time. As such a 4 to 6 hour window for re-opening the facility to traffic is frequently the target.

At this time it should be noted that the materials that may be used in new construction may not be the most ideal for use in a repair. Care must be exercised in choosing repair materials that are compatible with the substrate. The following section begins the discussion of some of the characteristics of an ‘ideal repair material’.

2.3: Characteristics of an Ideal Repair Material

Choosing the optimal repair material is not an easy task. Repair materials may have dramatically different costs and performance levels. Before an engineer attempts to select a specific repair material it is essential that they take the time to consider what type of behavior they expect from the repaired facility (Emmons, 1993; Poston et al. 2001).

The expectations of the agency implementing the repair and the highway commuters can generally be divided into two stages: a) expectations during the implementation of repair, and b) expectations after the repair is complete. During the implementation one of the key issues is the time required for completing the repair and reopening the facility. Once

the repair process is complete, the primary expectation of both parties is that the repaired pavement or bridge deck will be long-lasting.

Before we can start the process of identifying the properties of an ideal repair material we need to define 'long-lasting' more rigorously. Figure 2.2 illustrates four specific areas of performance that need to be considered in choosing a repair material. First the repair material must be able to meet the structural requirements associated with carrying load and distributing stresses throughout the structure. This generally requires that the repair material is well bonded to the substrate and that the repair material has similar elastic modulus and similar or greater strength than the substrate. The second main requirement of a repair material is that it can be easily placed and cured under less than ideal conditions. This requires that the material flows easily and has sufficient time in which it is workable so that it can be placed by the work crew. For the rapid repair materials investigated in this work it is crucial that the materials do not set too quickly thereby providing insufficient time for placement. It is also important that once the material is placed it begins to develop strength quickly so that the structure can be re-opened. The third main performance requirement is related to the durability of the repair material. This specifically includes the volumetric stability of the repair material and its resistance to environmental degradation caused by chloride ingress or freezing and thawing. The final requirement is that the repair material will be able to be finished in such a way that it can provide a smooth ride yet safe surface for the user.

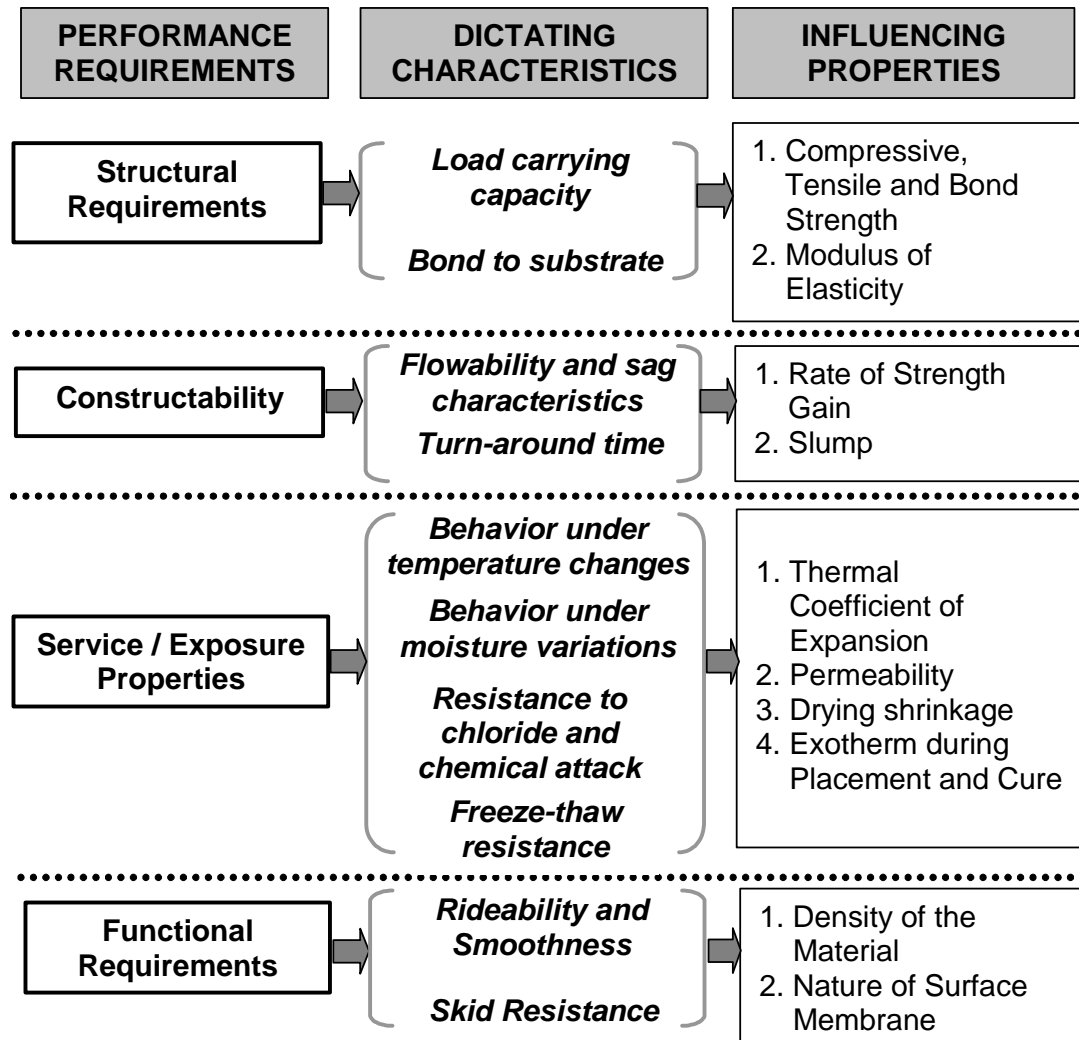


Figure 2.2: Characteristics of a Suitable Repair Material

While engineers frequently seek the use of stronger and stiffer materials for new construction, one of the greatest challenges facing the successful performance of repair materials is their ability to perform in harmony with the substrate material. Ebersom and Mays have provided the summary of properties of an ideal material in Table 2-1. Typically the repair material is expected to be atleast as strong as the parent material. This is meant to insure that the structure can carry the loads it was originally designed to

carry without a failure occurring in the repair material. It can also be seen that the modulus needs to be similar for both the repair and substrate material. This is due to the fact that when a load is added to composite system (i.e., the substrate material and the repair material) that the deformations and stress transmitted through each of these materials should be similar. In addition, the repair material should have properties that enable it to be dimensionally stable relative to the substrate (Emmons, 1993; Emberson and Mays, 1990; Poston et al. 2001). This frequently requires that the repair materials have a low drying and autogenous shrinkage and that these materials have a coefficient of thermal expansion that is similar to the substrate. Finally the material needs to bond well with the substrate.

It should be noted that the repair material should be designed to match the properties of the substrate at the time of the repair. As such the repair material may be expected to have values greater than the minimum design values of the structural design. At this time it should be noted that it is highly unlikely that a repair material will be found that behaves in exactly the same fashion as the substrate when subjected to loads, temperature and moisture changes. As a result the process of choosing an optimum repair material is a job of compromise (Emmons, 1993).

Table 2.1: Properties Governing Compatibility of Concrete Patch Repair (after Emberson and Mays, 1990)

Property	Relationship of repair material (R) to concrete substrate (C)
Strength in compression, tension and flexure	$R \geq C$
Modulus in compression, tension and flexure	$R \sim C$
Poisson's Ratio	Dependent on modulus and type of repair
Coefficient of thermal expansion	$R \sim C$
Adhesion in tension and shear	$R \geq C$
Curing and long term shrinkage	$R \leq C$
Strain capacity	$R \geq C$
Creep and Relaxation	Dependent on whether creep causes desirable or undesirable effects
Fatigue performance	$R \geq C$

2.4: Spalling and Common Reasons for Failure in Partial Depth Repairs

Spalling is a term that describes the cracking, breaking, chipping, or fraying of concrete slab edges at joints and cracks. Spalling is a common distress in jointed concrete pavements and bridge decks that decreases serviceability, and if left unrepaired, can become hazardous to roadway users (FHWA, 1999; Wilson et al. 1999). Several factors can cause spalling including (REMR Technical Note, 1994):

- the corrosion of reinforcing steel,

- inoperative joints resulting from incompressible materials in the joint,
- misalignment of dowel bars,
- impact to the pavement or bridge deck,
- freezing and thawing of water-saturated concrete, and
- alkali-silica reaction.

Once spalling has initiated it generally will continue to grow and propagate under repeated traffic loadings and thermal stresses (ACPA, 1998; United Facilities Criteria, 2001). For this reason, spalling is generally treated before it extends below the top third of the slab. Repairs of localized surface distress, such as spalling at joints and/or cracks in the upper one-third to one-half of a concrete pavement are generally referred to as partial depth repairs (Concrete Repair Manual, 1999).

Studies have shown that when partial-depth patches are properly installed using good quality control practices, 80 to 100 percent of the repairs perform well after 3 to 10 years of service (Webster et al. 1978; Snyder et al. 1989). However, in many cases, improper design and construction practices, combined with poor quality control and inspection, result in poor performance of the installed patches. Partial-depth spall repairs are susceptible to fail because of high shear stresses that develop between the substrate and the repair material. (Concrete Repair Manual, 1999). The common design and construction related parameters that can lead to the failure of a partial-depth patch are listed in Figure 2-4.

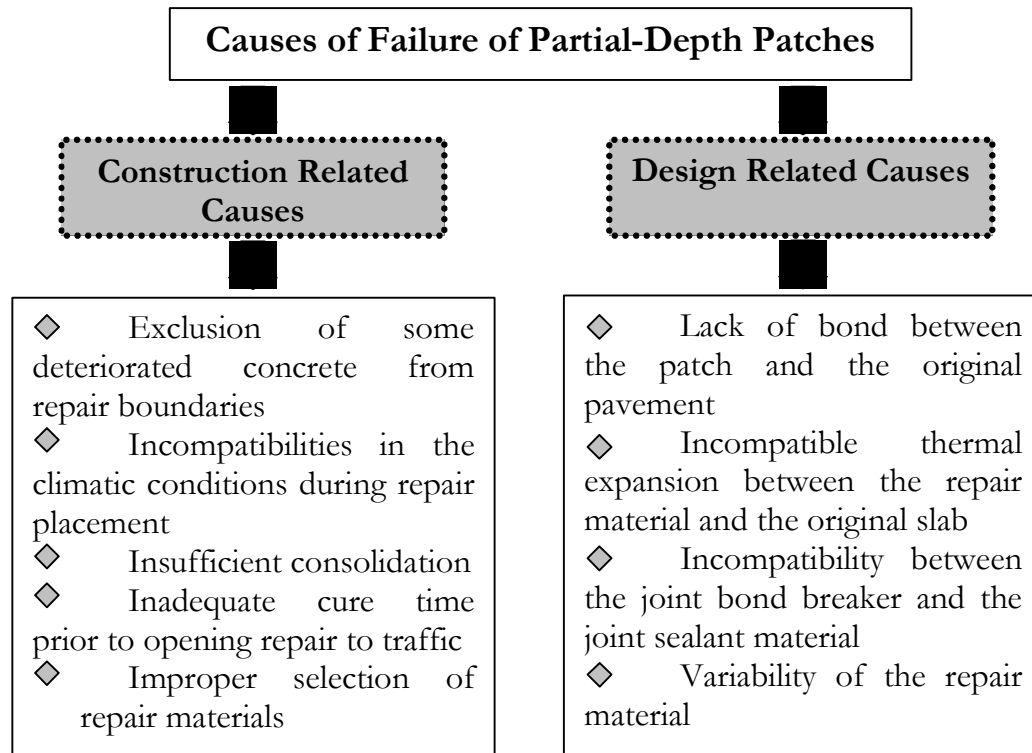


Figure 2.4: Factors Leading to Partial-Depth Repair Failures (Wilson et al. 1999)

A successful partial depth repair generally involves four main components (REMR Technical Note, 1994).:

- an inspection to document the extent and detail of the existing damage in a structure,
- an evaluation to determine the cause of distress and the as-constructed details for the damaged element,
- the selection of a repair material, and
- the application of the repair material in accordance with standard concrete practices or in accordance with the manufacturer's instructions for commercial products .

2.5: Classes of Repair Materials

Though properly designed, placed, and cured conventional portland cement concrete remains as one of the most reliable patching materials for concrete pavements (United Facilities Criteria, 2001), the repair performed with this traditional material necessitates detours or lane closures for extended periods of time. In an attempt to reduce the time required for repairs, the highway construction industry has seen a significant increase in the use of ‘rapid-set’ concrete patching materials.

Rapid-hardening cements are defined as those that can develop a minimum compressive strength of 20 MPa (3,000 psi) within eight hours or less (US Army Corps of Engineers, 1995), and are used to minimize out-of-service time for repairing pavements and bridge decks. These materials include concretes made with Type III portland cement, concretes containing regulated-set portland cement, gypsum-based concrete, magnesium phosphate concrete, and concrete containing high alumina cement (Baldwin and King, 2003).

A wide variety of rapid set patch repair materials are now available to the design engineer. These materials can be classified into three primary groups: cementitious mortars, polymer-modified cementitious mortars, and resinous mortars (Emberson and Mays, 1990; Cusson and Mailvaganam, 1996) as shown in Table 2.2 along with examples of the types of materials that would be classified in each of these groups.

Table 2.2: Generic Systems for Concrete Patch Repair (after Emberson and Mays, 1990)

GENERIC SYSTEMS FOR CONCRETE PATCH REPAIR		
Cementitious Mortars	Polymer-Modified Cementitious Mortars	Resinous Mortars
Portland Cement (PC)	Styrene Butadiene Rubber	Epoxy
High Alumina Cement (HAC)	Vinyl Acetate	Polyester
PC/HAC mixtures	Magnesium Phosphate	Acrylic
Expansion Producing Grouts	Acrylic	Polyurethane

The large number of commercially available repair materials with a wide variation in the mechanical properties makes the proper selection of a suitable patch repair material a daunting task (Cusson and Maivaganam, 1996). The material cost, shelf life, physical properties, workability, and performance also vary greatly among the different types of materials, and even from brand to brand within each type (Smith et al. 1991). The highway agency must determine which materials are suitable for a particular environment and working conditions as different materials have varying working tolerances, such as air temperatures and surface-wetting conditions during placement, mixing quantities and times, and maximum depths of placement (Wilson et al. 1999).

2.6: Material Properties and Their Relationship to Performance

Traditionally, the selection of an optimum patch material has been based on the data supplied by the manufacturers, who provide test results for relevant material properties. However, the manufacturers' data sheets provide little or no information about the long-term behavior and dimensional stability of rapid setting and high performance repair materials. Since relative dimensional changes can cause internal stresses within the repair material, substrate and at the interface, particular attention should be paid to minimize these stresses and to select materials that properly address relative dimensional behavior (Poston et al. 2001).

2.6.1 Mechanical Response

Typically the repair material is expected to be at least as strong as the substrate material. This is meant to insure that the structure can carry the loads it was originally designed to carry without a failure occurring in the repair material. It can also be seen that the modulus needs to be similar for both the repair and substrate material. This is due to the fact that when a load is added to composite system (i.e., the substrate material and the repair material) that the deformations and stress transmitted through each of these materials should be similar. Generally, if the material is to be used in a load bearing environment (i.e., a column or a beam) its creep should be low. It should however be noted that most repair materials, especially those used for repairs of spalling are in a fixed displacement condition and as such high creep helps to relieve residual stresses that may develop as described in the following section. Ansari et al. (1997) demonstrated that the

maturity method could be used to obtain reasonable assessment of strength development provided there was no pause in curing.

2.6.2 Volumetric Stability, Residual Stresses, and Debonding

One of the critical factors that dictate the success and durability of Partial-Depth Repair (PDR) in concrete pavements is the dimensional stability of the repair material. Dimensional incompatibilities between the repair material and the substrate in the form of differing elastic moduli and differing expansion and contraction due to thermal and hygral changes. These differential movements can cause the development of tensile stresses within the repair material or the substrate, leading to premature cracking, or can cause stresses at the interface leading to loss of bond between the repair material and the substrate (Randall et al. 2001). When a material is restrained from shrinking freely in response to a moisture or temperature change tensile stresses can develop in the material. If these tensile stresses become significant enough one of two things can happen, either the repair material can develop a tensile crack or it can debond. Examples of this are shown in Figure 2.5.

The magnitude of the tensile stresses that develop due to restraint calculated using Hooke's law ($\sigma = E\varepsilon$) are considerably higher than the actual stress levels. This phenomenon can be attributed to the beneficial effects of stress relaxation (creep). Thus, the free shrinkage test by itself cannot therefore predict if a concrete will crack in service though it is useful in comparing mixes of different compositions (Weiss et al. 1997).

Prediction of shrinkage cracking of concrete is a complicated phenomenon which depends upon many factors such as the shrinkage rate and magnitude, material stiffness, extent of stress relaxation, and the degree of restraint (Weiss et al. 1998). While several people have advocated the use higher strength materials to combat this problem, these materials frequently have higher modulus and lower creep which can actually increase their risk for early-age cracking (Shah et al. 1998).

If the material is strong enough to resist cracking but still exhibits high levels of shrinkage the material can develop high stresses between the repair material and the substrate. If these stresses are high enough interfacial cracking can occur resulting in delamination of the repair. The strength and integrity of the bond depends on not only the physical and chemical characteristics of the materials involved, but also on the surface roughness and workmanship (Austin et al. 1999).

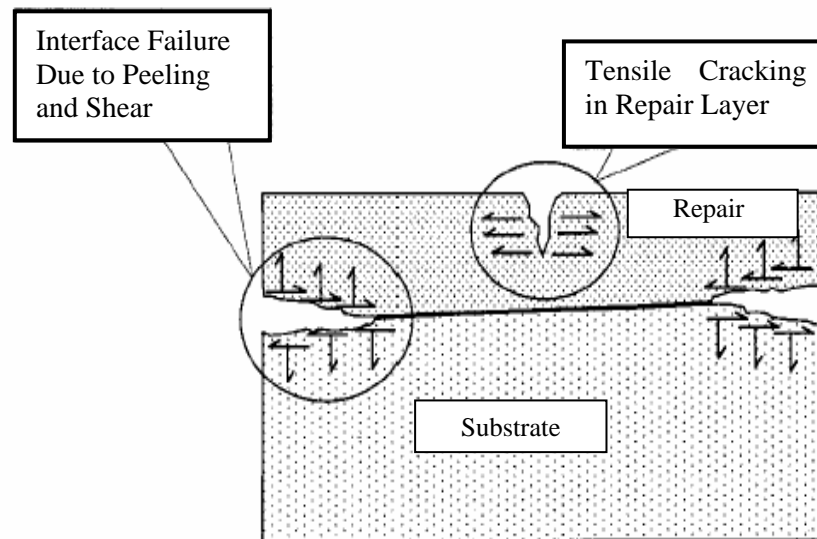


Figure 2.5 Primary modes of failure due to Volume Instability in Patch Repair (after Baluch et al. 2002)

Generally speaking it is desirable that a repair material develop sufficient bond with the substrate

2.6.3 Durability Due to Environmental Loading

The goal of the first phase of this project is to identify mixtures that show the appropriate mechanical performance for further analysis in a second phase of this study that investigates durability. While consideration of the long-term durability of these repair materials to surface scaling and freeze-thaw durability, and corrosion is important, it is beyond the scope of what will be covered in this report. It is generally believed that materials that behave well in standard durability tests (e.g., ASTM C666 for freeze-thaw, AASHTO 277 for chloride permeability) will generally behave well in the field. More details on the durability of repair materials can be found in the article by Paulson and Swilferbrand (1998).

2.7 Results of A Survey For INDOT Experience with Repair Materials

At the beginning of this project 20 surveys were sent throughout the state to the district directors, the Materials Engineer from each INDOT district, and industry representatives to determine which materials were most commonly currently used for repair. A detailed listing of the people surveyed is included in Appendix A of this report. Each person was mailed the survey attached in Appendix B of this report. This survey included 8 main questions which are listed in the following section and a summary of the responses to

these questions is listed in italics. Approximately 20% of the surveys were initially returned and a series of reminders increased the number of returned surveys to 30%. Some results from the surveys appeared to conflict indicating that there are different procedures used throughout the different districts in Indiana.

- Question 1: Please fill out the table as applicable describing the materials used for each type of repair, the procedures used for each type of repair, and the surface preparation procedures that you use in each repair condition.

The majority of the respondents to question 1 cited that they used bituminous materials for pot-hole patching and either a calcium chloride mixture, Mono-Patch, a latex modified concrete or Set 45.

- Question 2: What types of quality control testing do you typically use for repair materials?

The majority of the respondents to question 2 cited that they used either third point central loading or no quality control testing.

- Question 3: Are there any temperature/moisture restrictions on when you can perform repairs?

The majority of the respondents to question 3 cited that they either place these materials only when the temperature is above 32F, make special precautions to use heating blankets, or follow the manufactures recommendation for the temperature at the time of application.

- Question 4: How do you determine when the repair can be opened to traffic? Do you use cast-in-place specimens, maturity methods, etc.?

The majority of the respondents to question 4 cited that they either used the manufacturers recommendations or beams tested in third point loading to determine when a repair can be opened to traffic..

- Question 5: Are there any special procedures you use for curing the concrete or sealing the concrete?

The majority of the respondents to question 5 cited that they used a curing compound, wet curing or no curing.

- Question 6: Do you typically do repairs ‘in-house’, or contract out?

The respondents to question 6 cited both in house and contracted repairs.

- Question 7: Could you please indicate whether or not you have used the following repair materials and what your experience was with them. (It should be noted that question 7 included a listing of various repair materials that were obtained from the INDOT approved list and literature review).

The majority of the respondents to question 7 cited experiences with several different proprietary materials. Users of Mono-Patch cited that while it worked well, was easy to work with, and held up well that it was not used that frequently. Some users of Set 45 noted exceptional long term performance while one district mentioned some limited problems with shrinkage cracking at expansion joints. Users of Thoroc 10-60 mentioned that it was easy to work with while some districts had good experience with long-term performance others did not. Finally users of Duracal reported that while the material generally exhibited good performance it was difficult to work with and place.

While some useful information was obtained from the survey including peoples experience and information about the materials that were being used it can be seen that the response to each of these questions was generally somewhat variable.

2.8 Summary and Conclusions

In summary this chapter has reviewed the literature to describe many of the factors that are generally thought to contribute to good long-term performance of repairs and repair materials. Specifically, material properties were discussed as they relate to the choice of an ideal 'repair material'. It was illustrated that the repair material should generally have a similar or slightly higher strength than the substrate. The repair material should have a similar elastic modulus and unless the material is expected to carry large sustained load the material can benefit from its ability to creep or relax stresses. Repair materials need to bond well to the parent material and show volume stability when they are exposed to temperature or moisture changes. Finally, although durability properties are a key issue, they have not been described here other than to say that the fact that the repair material should observe performance under durability tests that would be similar to what would be expected from conventional materials.

CHAPTER 3: EXPERIMENTAL PROGRAM

3.1 Overview of the Research Program

The experimental program focused primarily on performing a materials characterization to determine the rate and the magnitude of mechanical property development in a wide range of repair materials. In addition, tests were performed to assess the bond strength and shrinkage. Understanding the rate of property development is important since if the reactions occur too quickly, sufficient time may not be provided to allow for the proper placement of the material, and this may result in development of high residual stresses. If the reactions are too slow, the material may not gain sufficient strength which may cause a delay in the opening of the structure. The following sections describe the materials, mixture proportioning, specimen preparation, and the various testing procedures conducted to evaluate the performance of the studied repair materials.

3.2 Materials

In order to conduct the necessary experimental program, samples of proprietary repair materials were requested from various manufacturers. In all, 22 companies were contacted, and 33 different repair materials were requested. Of those 33 materials, 11 were received. Table 3.1 lists each of the repair materials as well as the name of the manufacturer and the specimen label used throughout this report.

Table 3.1 Repair Materials, Manufacturers, and Specimen Labels

Repair Material	Manufacturer	Specimen Label
Baseline Mix	N/A	BASE
D.O.T. PATCH	Symons Corporation	DOTP
EMACO® T415	ChemRex®	EMACO
FX-928®	Fox Industries, Inc.	FX
High Performance Cement™	US Concrete Products	HPC
POLYPATCH	Symons Corporation	PPF
Rapid Road Repair	QUIKRETE®	QRRR
SET® 45 Regular*	ChemRex®	SET45
SET® 45 Hot Weather*	ChemRex®	SET45HW
Special Patch	Conspec® Marketing and Manufacturing, Inc.	SP
SikaSet® Roadway Patch 2000	Sika Corporation	SSRP
ThoRoc™ 10-60 Rapid Mortar*	ChemRex®	THOROC

*Denotes that these materials were on the INDOT approved list of Rapid Setting Patch Materials at the time that the project was started

Typically, the materials arrived in 50 or 55 pound bags or buckets containing both the binder and fine aggregates. Along with each material, the manufacturer sent a technical specifications sheet describing the details of mixture proportioning, the necessary equipment, and the proper methods of placement, substrate preparation, and curing of the repair patches. As noted in Table 3.1, three of the materials were listed on the INDOT list of approved Rapid Setting Patch Materials as of the time this study was initiated. In addition to the 11 proprietary repair materials, a mixture was prepared using ASTM type III Portland cement (manufactured by Lonestar Cement Co.) and 2% Calcium Chloride (by weight of cement) as an accelerator. This mixture is used as a baseline mixture for comparison purposes.

For each of the repair materials, a coarse aggregate extension was permitted based on the depth of the patch (or size of the test specimen). In all cases, the use of 3/8 in. pea gravel was permitted. The physical properties of the 3/8 in. pea gravel used in this work are shown in Table 3.2. Figure 3.1 shows the particle size distribution for this aggregate. The only two materials that required the addition of fine aggregates were the “High Performance Cement” and the baseline mixture. The physical properties of the fine aggregates are shown in Table 3.3 and the particle size distribution is shown in Figure 3.2.

Potable tap water was used as the mixing water in all of the mixtures except for the “Special Patch”. For this material, an acrylic polymer (named Special Bond) was shipped by the manufacturer along with the dry materials, and was used as the mixing liquid.

Table 3.2 Properties of 3/8 inch Pea Gravel Used to Extend All Repair Materials

Dry Rodded Unit Weight (lb/ft ³)	105
Dust Content (%)	2.54 (3.00% max per ASTM C-33)
SSD Absorption (%)	2.43
SSD Specific Gravity	2.64

Table 3.3 Properties of Fine Aggregate Used with High Performance Cement and Baseline

Fineness Modulus	2.9
Dust Content (%)	2.00
SSD Absorption (%)	1.80
SSD Specific Gravity	2.61

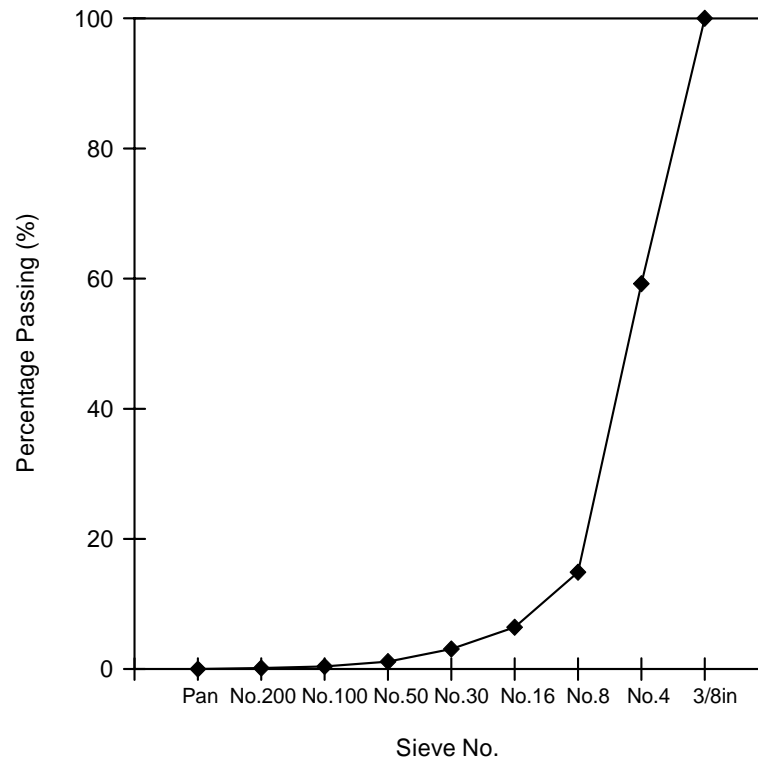


Figure 3.1 Particle Size Distribution for the 3/8 in. Pea Gravel

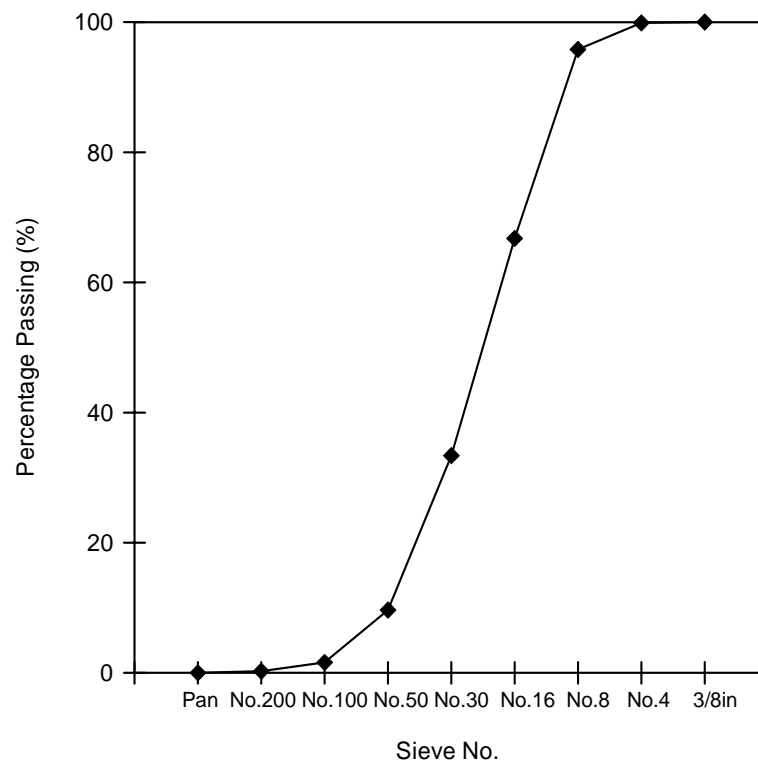


Figure 3.2 Particle Size Distribution for the Fine Aggregates

3.3 Mixture Proportioning and Specimen Preparation

The details of mixture proportioning, mixing, casting, and curing of specimens are presented in this section. The technical specification sheet of each material was strictly followed during the preparing and testing of the specimens.

3.3.1 Mixture Proportioning

The water and coarse aggregate contents of each mixture was prescribed by the specification sheets. A summary of the mixture proportions are presented in Tables 3.4 and 3.5. For the materials that arrived as prepackaged cement and fine aggregate, the amounts shown in Table 3.4 corresponds to one bag/bucket of material (generally 50 or 55 lb). The coarse aggregate extension (pea gravel) is shown as percentage by weight of the prepackaged material. For the “High Performance Cement” and the baseline mixture, the amounts shown in Table 3.5 correspond to a combined weight of 50 lbs of cement plus fine aggregates (to allow an easy comparison with Table 3.4). The mixing water of each mixture was adjusted to account for the moisture content of the aggregates.

Table 3.4 Mixture Proportions for the Materials Prepackaged as Cement and Fine Aggregate

Repair Material	Amount of Prepackaged Material (lb)	Coarse Aggregate (%)	Water (lb)	Mixing Time (min)	Total Allowable Working Time (min)	Curing	Consolidation
DOTP	50	30	7.30	5**	10	Moist	Hand Rodding
EMACO	55	54.5	4.19	3	10	Moist	Vibration
FX	50	60	7.09	2	15	Moist	Vibration
PPF	50	60	6.61	3 to 5	15	Moist	Hand Rodding
QRRR	50	50	6.17	4 to 5	20	Dry	Hand Rodding
SET45	50	60	4.19	1 to 1.5	10	Sealed	Hand Rodding
SET45HW	50	60	4.19	1 to 1.5	10	Sealed	Hand Rodding
SP	50	60	7.25*	2 to 3	20	Moist	Vibration
SSRP	50	50	5.21	5**	15	Moist	Vibration
THOROC	50	50	5.73	3	10	Moist	Vibration

*Special Bond acrylic polymer (included) was used instead of water

**Not specifically addressed by technical specification sheet; mixing time kept under 5 minutes

Table 3.5 Mixture Proportions for the Non-prepackaged Materials

Repair Material	Cement (lb)	Fine Aggregate (lb)	Coarse Aggregate (lb)	Water (lb)	Mixing Time (min)	Total Allowable Working Time (min)	Curing	Consolidation
BASE	19.94	30.06	45.06 (90%)	7.98*	N/A	N/A	Moist	Vibration
HPC	16.67	33.33	33.33 (67%)	5.84	3	15	Moist	Vibration

*2% calcium chloride by weight of cement was added to the mix water

3.3.2 Mixing Procedures

To determine the optimum mixing procedure, several different techniques were tested. It was observed that a well mixed and homogenous mixture can be obtained by using a slow-speed (0 ~ 335 rpm) right-angle hand-drill with a 5 inch tall mortar mixing paddle. To determine the optimum size of the mixing pan, trial mixtures of approximately 0.6 ft³ (1 bag of repair material plus 60% coarse aggregate extension) of “SET 45 Regular” repair material (selected arbitrarily) were prepared in three different mixing pans; a 6-gallon bucket, a 10 gallon bucket, and a 13-gallon pan (obtained by cutting and using the bottom 15 inches of a 55-gallon plastic aggregate drum). A number of 4 × 8 in. cylinders were casted from each mixture to be tested for compressive strength. The cylinders were tested at different ages; 1, 2, 4, 8, 12, and 24 hours, and 3, and 7 days, and the results are shown in Figures 3.3 to 3.5. The 6-gallon and 10-gallon pans were too small to allow sufficient mixing during the limited time permitted by the specifications. As a result, the specimens obtained from these mixtures exhibited an inconsistency in strength development as seen in Figures 3.3 and 3.4. On the other hand, the mixture prepared in the 13-gallon pan was mixed properly and showed a more acceptable trend in strength development (Figure 3.5). The results presented herein show that the property development in repair materials is highly influenced by the mixing procedure. This may explain to some degree why these repair materials frequently exhibits different levels of performance in the field.

As with the mixture proportioning, the prescribed mixing procedures were different for different repair materials. The recommended time of mixing varied between 1 and 5 minutes as shown by Tables 3.4 and 3.5. Generally, the water was added first, followed by the coarse aggregate, and

the bagged materials (cement + fine aggregate). For the baseline mixture, calcium chloride crystals were dissolved in the mixing water prior to the mixing.

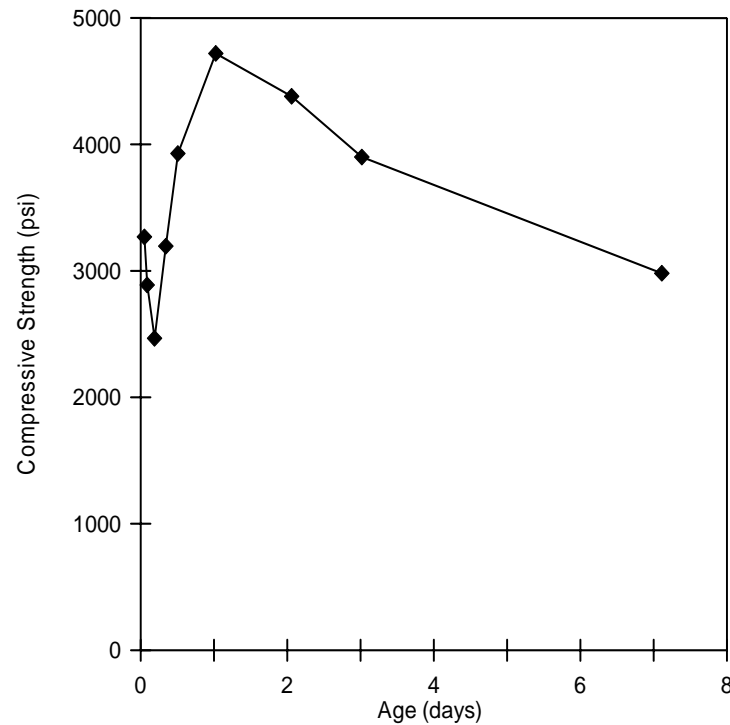


Figure 3.3 Compressive Strength Development for Preliminary Testing Trial 1 Noting Inconsistencies Due to Inadequate Mixing

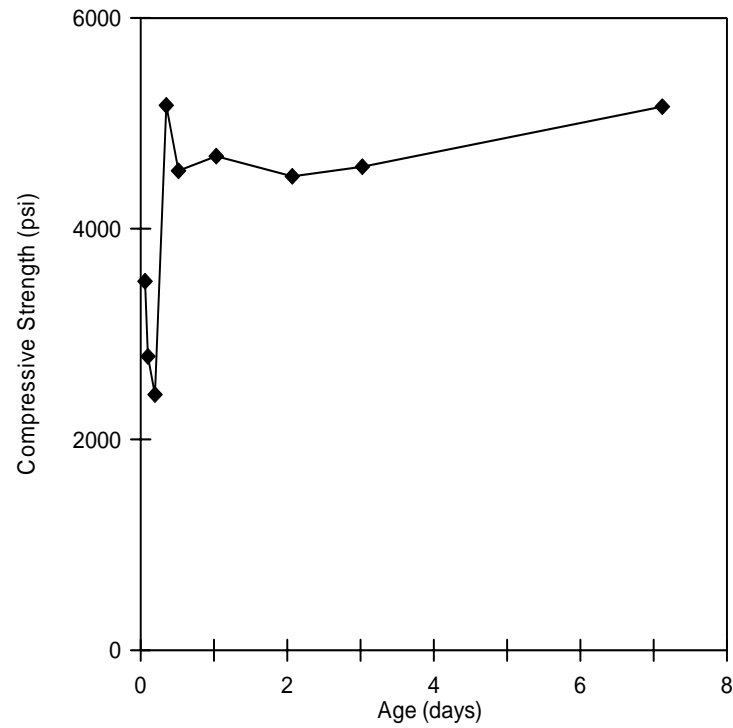


Figure 3.4 Compressive Strength Development for Preliminary Testing Trial 2 Noting Inconsistencies Due to Inadequate Mixing

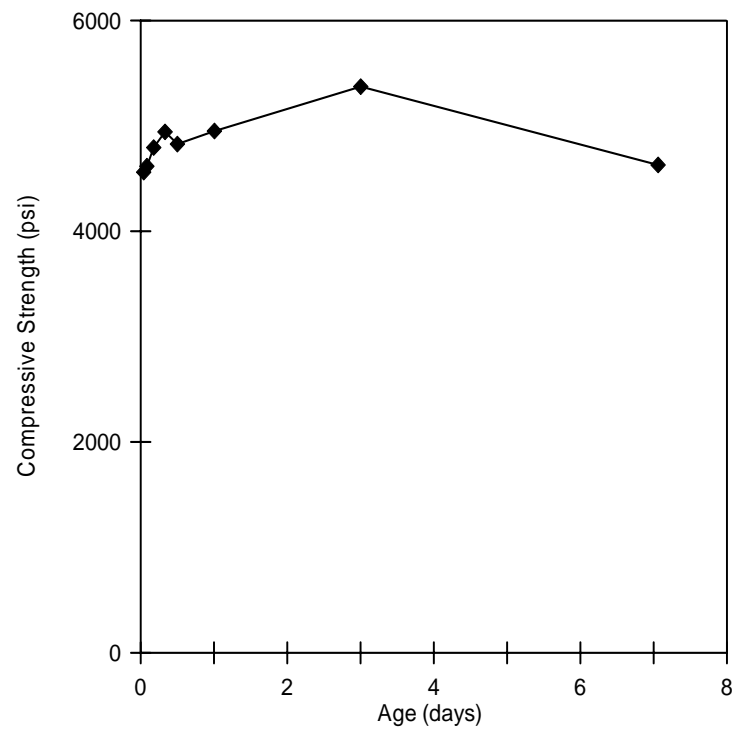


Figure 3.5 Compressive Strength Development for Preliminary Testing Trial 3

3.3.3 Specimen Preparation and Curing

After mixing, concrete was placed in forms and consolidated using hand rodding or internal vibration (Tables 3.4 and 3.5). If the material was considered self-leveling or internal vibration was strictly prohibited by the specifications, hand-rodding and tamping was used. The forms were covered by wet burlap to prevent moisture loss from specimens. After setting, the samples were demolded. Different curing procedures were applied according to the specifications (Tables 3.4 and 3.5). Moist curing was performed in a moist room with a relative humidity of $98 \pm 2\%$. Sealed curing was performed by sealing the specimens with plastic sheets. All samples were kept at room temperature ($23 \pm 1^\circ\text{C}$) except the specimens used for determination of the activation energy.

3.4 Experimental Procedures

3.4.1 Compressive and Flexural Strength

Compressive strength tests were performed in accordance with the procedure of ASTM C-39; “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens”. Two 4×8 in. cylinders were tested for each age. The cylinders were loaded at a rate of 35 psi/sec (26,400 lb/min) until failure. To better evaluate the rate of strength development (specially at early ages), compression tests were performed at early ages (1, 2, 4, 8, 12, and 24 hours), and at later ages (3, and 7 days). For some specimens, however, the 1 hour test was not feasible since the concrete was not yet set.

Flexural strength tests were performed in accordance with the procedure of ASTM C-78, “Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)”. The specimen size was a $3 \times 3 \times 15$ in. concrete beam. The clear span between the end supports was 12 in. Again, two beams were tested at each age. Prior to testing, a felt tip marker was used to mark the location of the end supports and the point load at the mid-span. The beams were loaded at a specific rate to increase a stress of 150 psi/min (338 lb/min) in the bottom fiber (maximum tension) of the beam. Similar to compressive strength test, flexural strength test was performed at 1, 2, 4, 8, 12, and 24 hours, and at 3, and 7 days of age. Again for some specimens, the 1 hour test was not feasible since the concrete was not yet set.

3.4.2 Static Elastic Modulus

Static elastic modulus test was performed in accordance with the procedure of ASTM C-469, “Standard Test Method for Static Modulus of Elasticity and Poisson’s Ratio of Concrete in Compression”. Static elastic modulus test was performed at 1, 2, 4, 8, 12, and 24 hours, and 3, and 7 days of age (one sample per age). The 4×8 in. cylindrical specimen (similar to the specimens used for compressive strength test) was fixed in a standard compressometer. The specimen was loaded three times at a rate of 35 psi/sec (26,400 lb/min). The first loading cycle was to properly “seat” the specimen in the compressometer and prevent any extraneous deflection during the subsequent loadings. In the second and third loading cycles, the following measurements were performed respectively; the load corresponding to a longitudinal strain of 50 micro strain, and the longitudinal strain corresponding to the 40% of the ultimate load. These measurements are needed to calculate the static elastic modulus of the specimen. After the third cycle, the sample was removed from the compressometer and used for compressive strength test.

3.4.3 Activation Energy

As a part of the “Maturity Method” (theoretical details discussed in Chapter 4), the activation energy for each mixture was measured according to the procedure described in Annex A1 of ASTM C-1074, “Standard Practice for Estimating Concrete Strength by the Maturity Method”. The procedure was to measure (at different ages) the compressive strength of 2 x 2 x 2 in. mortar cubes cured at three different temperatures. The curing temperatures were selected to be 2°C, 23°C, and 35°C to cover the range of temperatures usually expected in the state of Indiana. The compressive strength of the rapid repair mixtures was measured at 6 different ages; 1, 2, 4, 8, 12, and 24 hours. For the baseline mixture, the test was performed at 3, 4, 6, 12, 24, and 72 hours due to the delay in the setting time of this mixture relative to the rapid repair mixtures. As would be expected, some of the mixtures exhibited a delay in the setting time when cured at a low temperature. Accordingly, the first compressive strength test was postponed until the cubes had gained sufficient strength to be removed from the forms.

The specimens were casted using standard plastic mortar cube forms that house three cubes per mold. Prior to mixing, the dry materials and the mixing water (or the Special Bond) was stored overnight in environmental chambers with controlled temperature as required by the specifications. After casting, the molds were returned to the environmental chambers to control the specimens curing temperature. After setting, the cube specimens were demolded and sealed in plastic sheets, and returned to the environmental chambers. For each specimen, compressive strength test was performed according to the procedure of ASTM C-109, “Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube

Specimens)". The loading rate was adjusted to 200 lb/sec. The specimens were loaded to failure and the ultimate load was recorded.

3.4.4 Setting Time

The time of setting was measured according to the procedure of ASTM C-403, "Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance". The procedure is to measure the resistance of fresh mortar against 1 inch penetration of a standard needle. In this study, a standard penetrometer with an analog gage was used. A series of needles with surface area of 1.0, 0.5, 0.25, 0.10, 0.05, and 0.025 in² were used. The fresh mortar was casted in 6 x 6 in. plastic cylinders. For each mixture, two cylinders were casted. The test started within 10 to 20 minutes after the addition of water to the cement. Initially, the measurements were performed using the 1.0 in² needle. The test was repeated every 1 ~ 3 minutes based on the rate of increase in the penetration resistance. After the penetration resistance had increased beyond the loading capacity of the penetrometer, the penetration needle was replaced with the next (smaller) size. For each measurement, the age of mortar, penetration resistance, and the needle number were recorded. Measurements continued at regular intervals until the mortar gained sufficient strength so as to resist the penetration of the 0.025 in² needle.

3.4.5 Temperature Measurement

Temperature measurements were performed to monitor the heat evolution during the hydration process. The 4 x 8 in. cylinders were cast and cured at room temperature (23 ± 1°C). A type-T (copper-constantan) thermocouple was used and placed in the center of each cylinder. The specimens were sealed for the duration of the test. Measurements were automatically taken by a

Campbell Scientific CR10X data logger at five minute intervals (the average temperature over a 30 second window was recorded at every 5 minute). The measurements continued until the specimen's temperature reached equilibrium with its surrounding environment. The proprietary (rapid repair) materials usually reached equilibrium within 24 hours. For the baseline mixture, the measurements continued for 3 days.

3.4.6 Early-Age Volume Stability (Autogenous Shrinkage)

Measurements of early-age volumetric changes were performed using a non-contact laser device developed at Purdue University. Details regarding the equipment and the testing procedure are discussed elsewhere (Pease et al. 2004). However, Figures 3.6 and 3.7 provide an illustration of the experiment. A laser beam is emitted from a source and reflected back from the surface of the specimen (Figure 3.6). The semiconductor (CMOS/CCD) detector is sensitive to the reflected laser beam and can be used to determine the position of the reflecting surface (i.e. specimen). The measurements are controlled by a special computer software developed using LabVIEW™ (V6.0; National Instruments). This technique can be used to measure length changes in a concrete specimen even prior to setting (plastic phase).

In this study, specimens of the rapid repair mixtures were cast in a Lexan® plastic form with inner dimensions of $3 \times 3 \times 10$ in. (Figure 3.7). The form was sealed in the duration of the test. Two non-contact laser systems were used to measure the length changes of the plastic concrete specimen from both ends. The form had holes at both ends to allow the laser beam to pass through and hit the specimen's surface. Initially, these holes were covered with a thin film of acetate (transparent to laser beam) to prevent the plastic concrete from seeping out of the form.

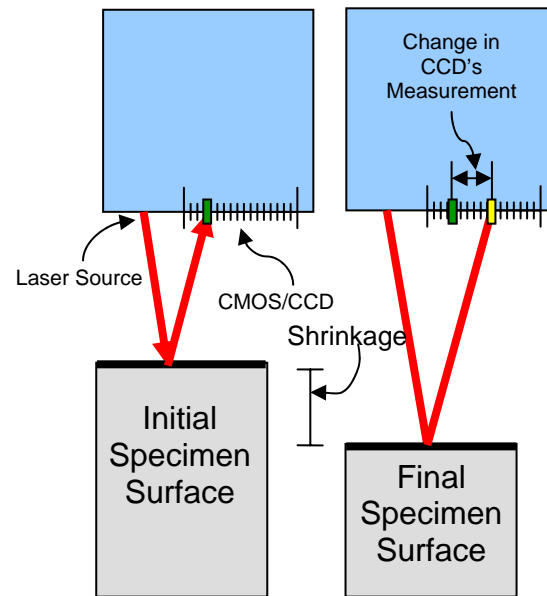


Figure 3.6 Illustration of How Laser Probes Measure the Distance to the Concrete Specimen by Sending a Laser Light Beam that Is Reflected From the Specimen and Recorded by A Ceramic Metal Oxide Semi-Conductor (Pease et al. 2004)

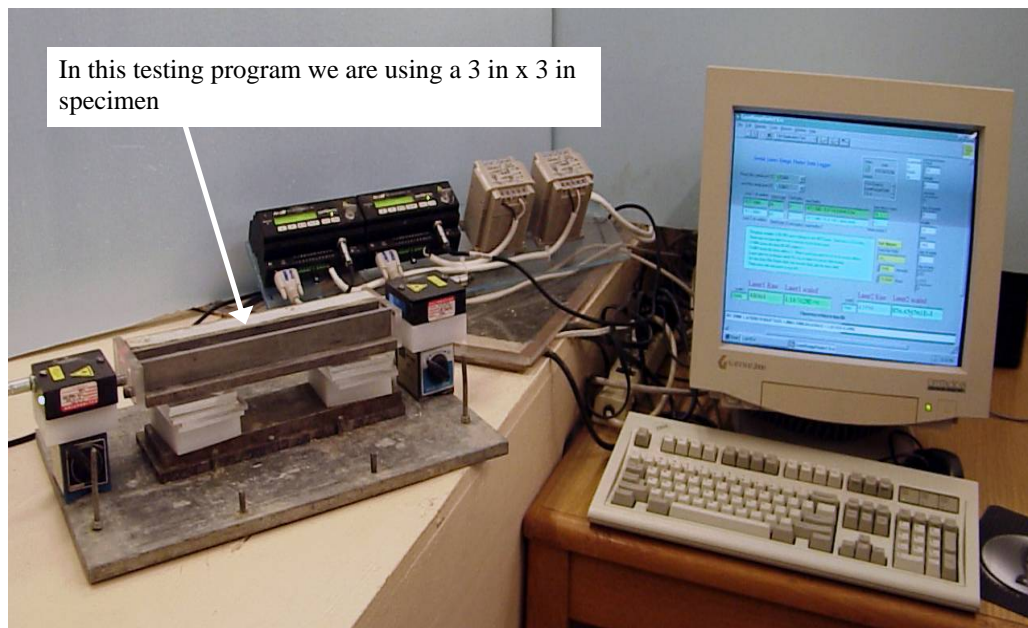


Figure 3.7 A Photograph of the Laser Setup Which Was Used for Measuring Early-Age Volume Changes In the Repair Material (Pease et al. 2004)

As mentioned, this procedure allows length measurements to begin immediately after casting, while concrete is still plastic. The test was performed at room temperature (23 ± 1 °C) and continued until and after concrete's setting. For the rapid repair mixtures the test terminated at 6 hours of age while it was continued until 9th hour for the baseline mixture. Further length changes were monitored using the procedure described in the following section.

3.4.7 Later-Age Volume Stability (Autogenous and Drying Shrinkage)

Parallel to the early-age laser tests, specimens were prepared and tested to obtain later-age (after 6 or 9 hours) length changes. The experiment was performed according to the procedure of ASTM C-157, "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete". For each mixture, four $3 \times 3 \times 11$ in. samples were prepared with embedded gage studs on each end to facilitate the length change measurements using a comparator. The specimens were sealed after casting by covering the molds with plastic sheets. The specimens were demolded after 6 hours (rapid repair mixtures) or 9 hours (baseline mixture). After demolding, two of the specimens were completely sealed using two layers of a self-adhesive aluminum tape to provide a measure of autogenous shrinkage. The other two specimens were sealed only on two opposite faces to enforce one-dimensional drying. This helps avoiding difficulties in data interpretation caused by the development of a complex moisture gradient at corners due to drying from two perpendicular surfaces (two-dimensional drying). An initial length measurement was made, immediately after demolding and sealing. A standard comparator (manufactured by Humboldt) with an accuracy of ± 0.0001 in. was used for length change measurements. After the initial measurement, the specimens were placed inside an environmental chamber with a constant temperature (23°C) and relative humidity (50%).

Later length measurements were performed approximately every 12 hours for the first 3 days, every day up to 7 days, and then every 7 days up to an age of 28 days in order to establish a detailed shrinkage/expansion profile.

3.4.8 Restrained Shrinkage

The measurements performed in the two preceding sections, enable obtaining the shrinkage behavior of the material in the absence of any external restraint (i.e. free shrinkage). Restraining this shrinkage causes development of tensile stresses inside the material that can lead to cracking. To assess the stress development and the cracking potential of each material (due to restrained shrinkage), a series of restrained ring specimens were prepared and tested according to ASTM C-1581, “Standard Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage”. The procedure was to cast an annulus of concrete around an instrumented steel ring. The steel ring was instrumented with four strain gages installed on to its inner surface. The strain gages were connected to a data acquisition system in a quarter-bridge configuration and the strain data was acquired at 2 minute intervals (Figure 3.8; Hossain et al. 2002).

The steel rings had a wall thickness of 3/8 in. and a height of 3 in. The concrete ring had a height of 3 in. and an inner diameter of 12 in. and an outer diameter of 18 in. An 18-in. Sonotube™ cardboard ring was used as an outer wall to support the concrete prior to setting. After casting, the specimens were covered with plastic sheets and placed inside an environmental chamber ($23 \pm 1^\circ\text{C}$, $50 \pm 2\%$ RH). The specimens were demolded after setting (6 or 9 hours), and placed back inside the environmental chamber. The outer circumference of the rings was

sealed using the aluminum tape to limit the drying to the top and bottom surfaces, consequently causing a uniform moisture profile to develop across the radius of the concrete ring. The strain measurements were continued for 7 days.

As shown later in this report, the strain measurements from the steel ring can be used to calculate residual stresses that develop inside the concrete ring. However, it should be noted that this test cannot monitor the possible expansion in the concrete ring which may happen for rapid repair mixtures. In this case, extra care must be taken in the interpretation of results.



Figure 3.8 Data Acquisition System for Monitoring Strains in Restrained Rings

3.4.9 Bond Strength

The strength of the bond between the repair patch and the substrate concrete was evaluated using two different tests. The first test involved measuring the pull-out, or tensile force required to

separate the repair material from the substrate. The second test involved applying a direct shearing force at the interface between the repair and substrate concrete. Both tests were applied to two different types of surface roughness; a smooth surface obtained by saw cutting the substrate, and a rough surface obtained by fracturing the substrate along a predetermined plane. It should be noted that the rough surface is a better representative of the actual field conditions, in which the deteriorated concrete is usually removed by pneumatic hammers, hand tools, water blasting, or similar techniques, thereby providing a rough substrate.

For this study, the substrate concrete was made using Type I portland cement (produced by Lonestar Cement Co.), with $w/c = 0.40$, and 70% aggregate by weight, of which 60% was coarse aggregates (crushed limestone with a maximum size of 1 in.), and 40% was fine aggregates (a locally available river sand). The substrate concrete was mixed and cast according to the procedure of ASTM C-192, "Practice for Making and Curing Concrete Test Specimens in the Laboratory". After casting, the specimens were placed in a 98 ± 2 % RH moist room for curing for 7 days.

For the pull-out test, four 3-inch diameter cylindrical repair patches were cast on the top of a $3 \times 6 \times 20$ in. substrate slab (Figure 3.11). The substrate slab was prepared differently based on whether a rough or a smooth surface was desired. To prepare a rough substrate, a $6 \times 6 \times 20$ in. form was filled with concrete up to about its mid-height, a thin piece of Styrofoam ($3/8^{\text{th}}$ in. thickness) with four 3-inch diameter circular holes was placed on top of the concrete, and the remaining of the mold was filled with concrete. Using this procedure, a $6 \times 6 \times 20$ in. concrete beam was prepared with an embedded layer of Styrofoam. The Styrofoam was placed inside the

specimen to produce a weak plane that could be used for fracturing the specimen into two halves with four cylindrical fracture surfaces (Figure 3.9). After 7 days of age, the specimen was fractured using a loading wedge.

To prepare a smooth surface, a $6 \times 6 \times 20$ in. concrete slab was cast and after 7 days of curing was cut into two halves using a diamond-tip wet saw (Figure 3.10).

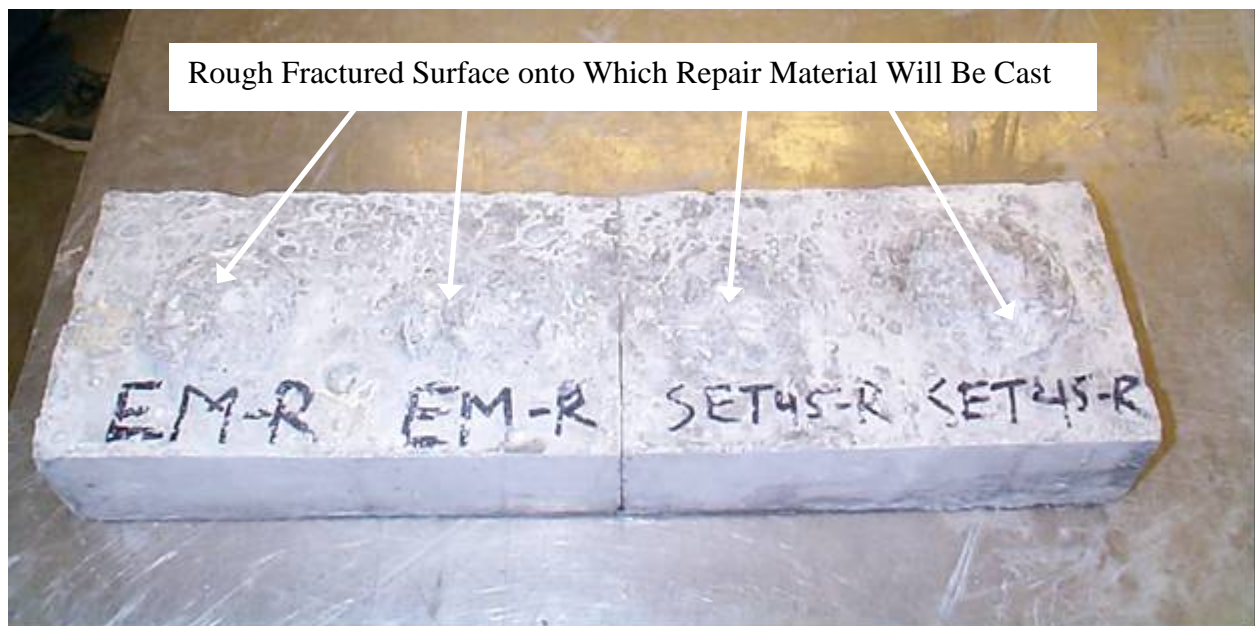


Figure 3.9 Typical Rough Substrate Slab Used in Pull-out Bond Testing

To cast the repair patch on the top of the prepared substrate, four 3 x 3 in. plastic cylinder forms were installed on the top of the substrate specimen using a silicone caulk (Figure 3.11). The repair mixture was casted inside the plastic cylinders and allowed to cure under the prescribed conditions for 6 days. After curing, a 3 in. diameter steel disc with a welded nut on the top was glued on top of the repair patch to facilitate the application of the tensile load. The steel disc was glued to the repair patch using a high strength epoxy, which was allowed to cure for an

additional 24 hours. To aid the bonding of the epoxy to the repair patch, the surface of the patch was roughened by brief sandblasting prior to applying the epoxy.

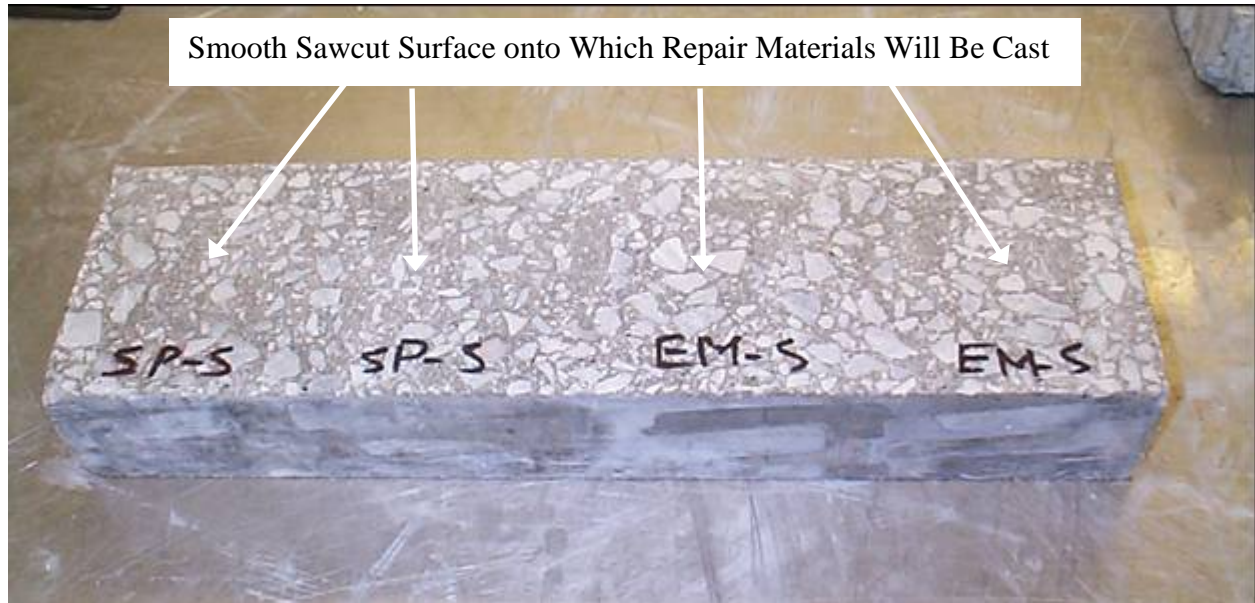


Figure 3.10 Typical Smooth Substrate Slab Used in Pull-out Bond Testing



Figure 3.11 Substrate Slab with Attached Cylinder Forms for Pull-out Bond Testing

The tensile load was applied using a “007 James Bond Tester”, manufactured by James Instruments, Inc. The equipment had a “pull bolt” that was threaded into the welded nut of the steel plate. The load was applied by turning a hand crank at the top of the tester. The load gauge on the tester was capable of measuring up to 4500 lb load and was equipped with a maximum-load indicator. The tensile load was applied until failure. The maximum load was recorded as well as the location of the failure plane; within the repair patch, at interface, within the substrate, or any combination of these.

For the shear bond test, 4×8 in. cylindrical specimens were prepared having a half-height substrate and a half-height repair layer (Figure 3.14). Initially, 4×8 in. substrate cylinders were cast. To obtain a smooth surface, these cylinders were cut into halves using a diamond-tip wet saw. To get a rough surface, a small notch was cut at mid-height of the cylinder, and then the cylinder was fractured in flexure using single-point loading. Figure 3.12 shows two prepared substrate specimens. As with the pull-out substrate slabs, the substrate cylinders were cut or fractured after 7 days of moist curing.

To cast the repair patch on the top of substrate specimens, a 4×4 in. plastic cylinder mold was installed on the top of each substrate cylinder using ordinary duct tape (Figure 3.13). The repair patch was then cast into the molds and cured under the prescribed conditions for 7 days (Figure 3.14).

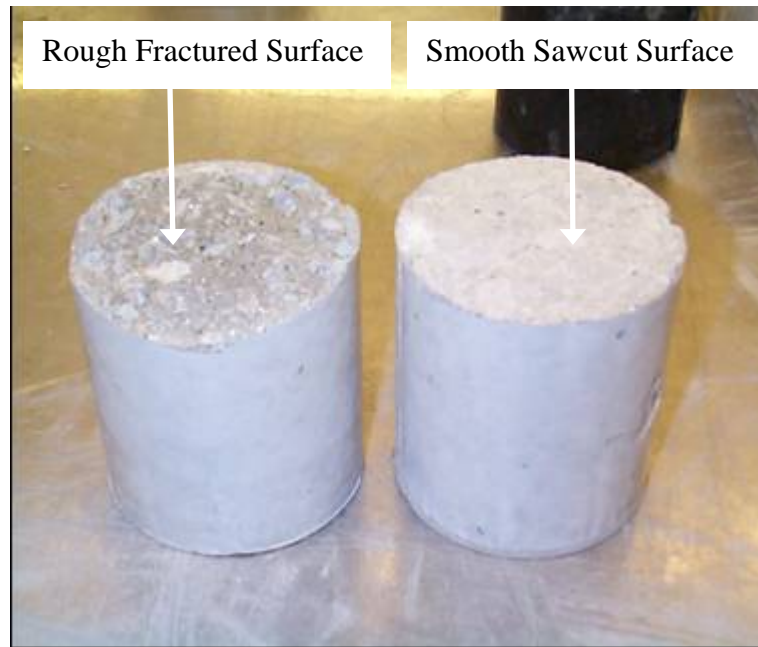


Figure 3.12 Rough and Smooth Substrate Cylinders Used in Shear Bond Testing



Figure 3.13 Substrate Cylinder with Attached Cylinder Form for Shear Bond Testing

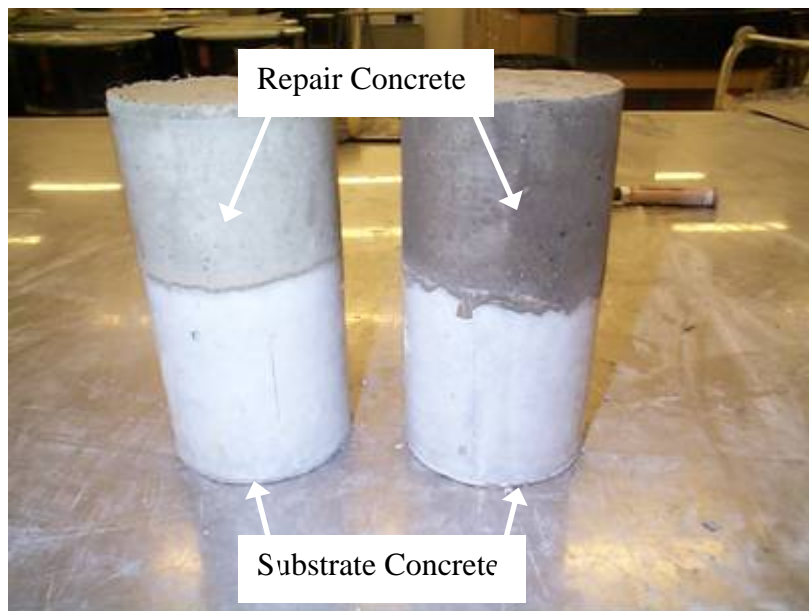


Figure 3.14 Substrate Cylinders with Bonded Repair Cylinders for Shear Bond Testing

The shear test was performed using a loading jig similar to the device developed by the Iowa Department of Transportation (IOWA Shear Test); Figure 3.15. This jig was designed to test a 4-in. diameter cylinder in shear. The jig was placed inside an MTS machine that applies a controlled tensile force, thereby pulling the two sides of the jig apart, and applying a controlled shear force to the cylinder. The cylinder was placed in the jig in a way that the repair-substrate interface was between the two sides of the jig. The loading was continued until the failure of the specimen. The ultimate shear strength was recorded as well as the location of the failure plane; within the repair patch, at interface, within the substrate, or any combination of these.

In addition, the split tensile strength of the substrate concrete was measured from 4×4 in. cylinders according to the procedure of ASTM C-496, “Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens”. The loading rate was set to 200 psi/min (~ 5000 lb/min). A total of 5 cylinders were tested after 7 days of moist curing.

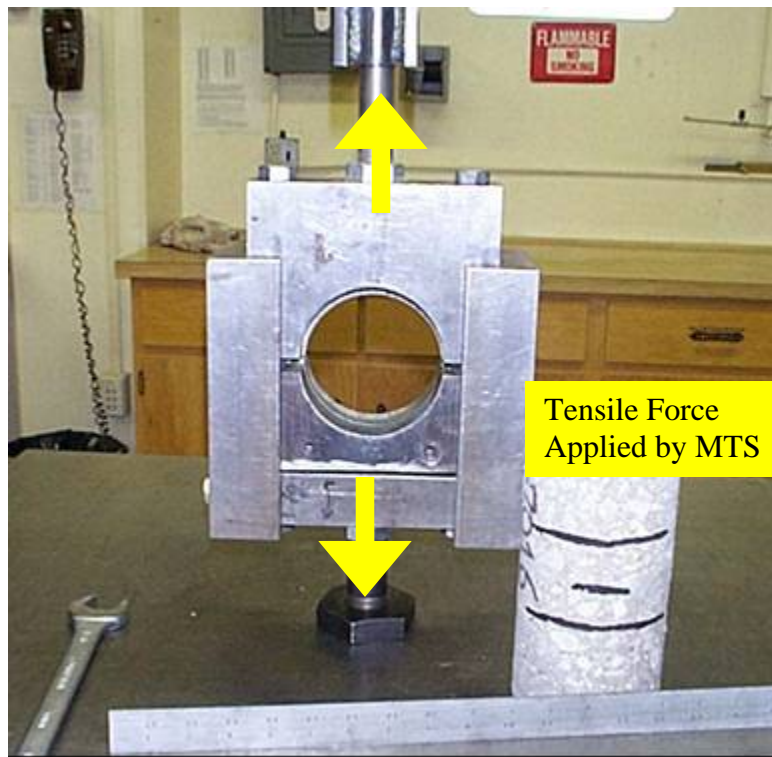


Figure 3.15 Testing Jig Used to Shear the Substrate-Repair Cylinders

3.4.10 Ultrasonic Pulse Velocity Measurement

The velocity of an ultrasonic pulse inside hardened concrete was measured for each of the mixtures according to the procedure of ASTM C-597, “Standard Test Method for Pulse Velocity through Concrete”. The procedure is to generate an ultrasonic compression wave through the concrete specimen and measure the travel time of the wave across the specimen. A V-meter manufactured by James Instruments, Inc. was used for these measurements. This V-meter included a pulse generator, a time measurement circuit, a receiver amplifier, and a time display unit. The accuracy of the measurements was $\pm 0.1 \mu\text{s}$. Two 2.2×2 in. transducers were used to generate and receive the pulse. The generated pulse had a frequency of 37 kHz. A series of 4×8 in. concrete cylinders were prepared for this test. The specimens were cast inside plastic molds

with removable top and bottom parts. This allowed measuring the pulse velocity without a need to demold the specimens. Prior to testing, a standard automotive chassis grease was applied to each end of the concrete cylinders as a couplant to allow the sound waves to effectively transfer from the transducers to the concrete and vice versa. The measurements were started after the concrete was set. Measurements were taken every 10 minutes for the first hour, every half hour up to 4 hours, every hour up to 8 hours, and then at 10 hours, 12 hours, 1 day, 2 days, and 3 days.

3.5 Summary

Details of specimen preparation and testing procedures were described in this chapter. Standard procedures were used to measure the compressive strength (ASTM C-39), flexural strength (ASTM C-78), elastic modulus (ASTM C-469), setting time (ASTM C 403), activation energy (ASTM C-1074), free shrinkage (ASTM C-157), restrained shrinkage (ASTM C-1581), and ultrasonic pulse velocity (ASTM C-496) of 11 different rapid repair mixtures plus a baseline mixture for comparison purposes. Also, a non-contact laser system developed at Purdue University was used to measure the autogenous shrinkage of each mixture before the setting time. Finally the tensile and shear strength of the bond between a repair patch and the substrate concrete was measured for two different types of substrate surface preparation (i.e. smooth, and rough surfaces).

CHAPTER 4 THE MATURITY METHOD

4.1 Introduction

It is frequently essential to know the rate of strength development for a concrete or repair material. The maturity method has been widely implemented to predict the in-place strength of cementitious materials. This chapter describes the basic principles of maturity method and discusses its applications for strength development of rapid setting cementitious materials.

Section 4.2 provides a basic introduction of maturity method as an application for early age in-place strength prediction. The third section introduces the significant features of the “RoD – Rate of Property Development of Concrete”, (Barde 2004). Finally, the fourth section of this chapter explains a step-by-step procedure to use RoD.

4.2 Maturity Method

The maturity method is becoming more widely used by the construction industry to signal when certain construction operations like opening the traffic or removing the formwork can be performed. The basic concept of maturity method is rooted in the fact that strength development in cementitious systems is related to the extent of the chemical reaction (i.e., hydration) that has taken place. This chemical reaction is a function of the time and temperature history of the specimen (i.e., the reactions occur more rapidly at a

higher temperature) and it is frequently assumed that a unique relationship exists between strength and the product of time and temperature (i.e., maturity). Using thermocouples or thermistors, inserted in the concrete at various critical locations, the time-temperature history of concrete can be determined and recorded using a data logger. The time-temperature history is then used to calculate the maturity index (or an index of how old the concrete is compared to its age at a standard temperature) of the curing concrete.

Under isothermal curing conditions, the strength of the concrete is related to the maturity index by a hyperbolic curve (Tank and Carino, 1991). This hyperbolic curve is defined by three parameters: (1) the long-term strength, S_{∞} , (2) the rate constant, k_t , and (3) the offset age, t_0 . As its name implies the long-term strength is simply the ultimate strength that the concrete will attain at some very old age. This is also frequently referred to as the infinite strength or the ultimate strength. The rate constant describes how rapidly the reaction takes place and the offset age describes the time when rapid strength development begins. The detailed procedure to compute the above mentioned parameters is delineated in the subsequent sections.

In addition to just measuring the strength development at a constant temperature it is important to determine the activation energy, E_a of a material. This activation energy is defined as the energy required to initiate the hydration reaction and is useful for enabling maturity predictions at temperatures other than the standard isothermal lab conditions. The activation energy is used along with the Arrhenius equation to relate the effects of temperature with the rate constant (Carino 1991, Carino et al., 1983). Using these

parameters (i.e., long term strength, the rate constant, the offset age, and the activation energy) the hyperbolic strength development equation can be used to predict the strength of the given concrete mixture can be predicted for any time and temperature history.

Using the maturity method for predicting the rate of property development (from hereon the word property is used as opposed to simply strength since the maturity can be used to predict the development of other properties like the elastic modulus) of concrete uses two major steps. The first step of the process involves development of a master-curve which provides the relationship between the desired property and maturity using the controlled curing condition data (e.g., for most cases this is isothermal lab conditions with $23^{\circ}\text{C} \pm 1^{\circ}\text{C}$ and $98 \pm 2\%$ RH). The second step of the process involves calculating the maturity of the given field specimens using the variable temperature curing data (time-temperature history) and predicting the desired property using the model in step 1. Before demonstrating how the master curve is produced a brief background of the principles behind the maturity method are presented.

4.2.1 Property Development and the Maturity Method

The rate of property development can be written as (dS/dt) , where the desired property is designated as S (e.g., this can be compressive strength, elastic modulus, or flexural strength), at any age t , and is assumed to be a function of the temperature, T . It can be said that the rate of property development is simply a product of some function that describes the property and another function that describes the rate of the reaction which is temperature dependent as shown in equation 4.1

$$\frac{dS}{dt} = f(S).k(T) \quad (4.1)$$

where $f(S)$ is a function of the material property, $k(T)$ is a function of temperature, also called the rate constant. Based on experimental evidence, Bernhardt proposed a that the function of the desired property development could be written with a form like that shown in equation 4.2

$$f(S) = S_{\infty} \left[1 - \frac{S}{S_{\infty}} \right]^2 \quad (4.2)$$

where S_{∞} is the limiting value of desired property at an infinite age.

We can begin by assuming that the long term property (i.e., S_{∞}) is independent of curing temperature (this implies that irrespective of the temperature at which the specimen is cured, provided it is high enough to enable the chemical reaction to take place, the strength will, given enough time, eventually reach the same property). Substituting equation 4.2 into equation 4.1 and integrating gives the following expression:

$$\int_0^S \frac{dS}{\left(1 - \frac{S}{S_{\infty}} \right)^2} = S_{\infty} \int_{t_0}^t k(T) dt \quad (4.3)$$

where t_0 is the time at which the desired property starts to develop.

The right hand term $\int_{t_0}^t k(T)dt$ involves product of time and temperature and is denoted as the general form of maturity function.

Integrating left hand side of equation (3) yields the general strength maturity relationship:

$$S = S_{\infty} \left(\frac{\int_{t_0}^t k(T)dt}{1 + \int_{t_0}^t k(T)dt} \right) \quad (4.4)$$

4.2.1.1 Isothermal Temperature Curing Conditions

When the curing conditions are constant (i.e., the temperature is constant) the rate constant has a single constant value. As a result the hyperbolic property development equation can be written as:

$$S = S_{\infty} \left(\frac{k_t(t-t_0)}{1 + k_t(t-t_0)} \right) \quad (4.5)$$

This equation is commonly referred to as the master curve model. It can be compared to the results of experimental tests at a constant temperature and used to calculate the three reference values, the long-term ultimate strength (or long term ultimate property), the rate constant and the offset time. Details on how this is specifically done are provided in section 4.4.

4.2.1.2 Accounting for Varying Temperature and Rates of Reaction

While the relationship provided in equation 4.5 is useful for laboratory conditions it must be modified to account for the effect that varying temperature has on the rate of the chemical reaction. As previously mentioned this will be done by relating the rate constant to the arrhenius expression.

$$k(T) = \beta e^{\left(\frac{-E}{R(273+T)}\right)} \quad (4.6)$$

where E is the activation energy, β is a material constant, R is the universal gas constant and T is the temperature given in Celsius.

The Maturity index can be defined using equation 4.7

$$M = \int_0^t \left(\frac{k(T)}{k_r} \right) \quad (4.7)$$

where k_r is the rate constant at reference temperature.

As a result the relationship between the property development can be rewritten in terms of maturity as shown in equation 4.8

$$S = S_{\infty} \left(\frac{M - M_0}{1 + M - M_0} \right) \quad (4.8)$$

where M is the maturity, M_0 is the offset maturity (i.e, the maturity when the material begins to set and S_{∞} is the long-term strength.

To avoid repetitive computations, software has been developed at Purdue University to perform above mentioned calculations and prepare the master curve. The software can be further used to transform downloaded data from the dataloggers to calculate the maturity under varying curing conditions and to in turn use this information to estimate the desired property (e.g., strength at a given time). In addition this software can be used to simulate how any of the materials tested in this study will perform under different temperature histories in the field.

4.3 RoD - Rate of Property Development of Concrete

This chapter describes the software developed which is called the Rate of Property Development of Concrete (RoD). This section details the features and central idea behind the software development. The primary objective of this section is to provide the information about the ability of the software and the various options available to utilize it for maturity method calculations.

The sole purpose of the User Interface is to provide the user with a user friendly environment to calculate the desired maturity property relationship while having the

flexibility to control the selection of parameters and constants to achieve an accurate model. The program was developed to have a logical flow that resembles the steps used in solving the actual problem manually. In addition, the user is able to have the calculation results with the intention of enabling better representation of the actual testing data.

The program is divided in the various screens. Each of these screens will be explained in greater detail in Section 4.4.

1. Main Screen
2. Disclaimer
3. Units Screen
4. Choice for Data Source Screen
5. Message for successful Data Transfer
6. If Manual choice : Form for Manual Data Entry
7. Plot of S vs. $(1/\text{Time})$
8. Plot for $S/(S_{\infty} - S)$ vs. Maturity form
9. Plot of Master Curve
10. Choice screen for curing temperature conditions.
11. Calculator screen to predict the desired property.
12. Corresponding plot of S vs. Maturity for given data.
13. Various message and warning screens wherever required.

Figure 1 illustrates the initial screen which develops when the Rod Software is started. All of the operations will be completed within this window. The Menu Bar

(indicated by Arrow 1) gives the various choices such as Printing Report or Starting with a new set of calculations.

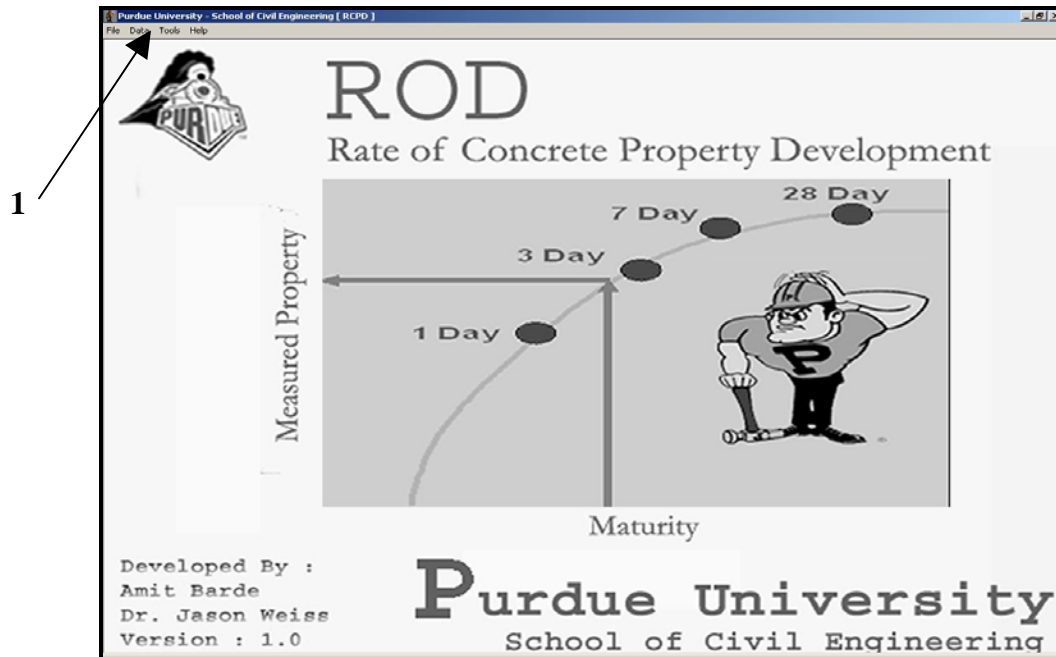


Figure 4.1 Main Interface Window Obtained on Starting the Rod Software

The Various Functions in Menu Bar and the uses are:

File: This is subdivided into:

New: Start working with new set

Exit: Exit the Program

Data: This allows to go to the data input screens.

Tools: This has been subdivided into:

Report: Allows to print a report consisting of the important calculations and graphs.

Help: This section provides the help sessions and information about the software.

The various main screens throughout the Software are:

- 1) Unit Screen:** User can define various quantities and constants that will be used for the calculations in this screen.
- 2) Data Input Choice Screen:** User has the choice of selecting the source of data either from a comma separated text format file or input it manually.
- 3) Plot of S vs. $(1/\text{Time})$:** This decides the value of S_{∞} . User is also given a chance to change this value according to personal judgment by controlling the data points to be considered for regression analysis.
- 4) Plot of $S/(S_{\infty} - S)$ vs. M :** This decides the values of M_0 and k_r . User is also given a chance to change this value according to his judgment by controlling the data points to be considered for regression analysis. M_0 is the Maturity at which the desired property starts to develop after mixing/placing. k_r is the rate constant at reference temperature.
- 5) Plot of S vs. Maturity:** This is the Master Curve and decides the model for relation between S and Maturity. This curve is used to find the desired property values corresponding to maturity or vice versa throughout the program.
- 6) Calculator Screen:** This allows the user to find the values of desired property corresponding to maturity or vice-versa.
- 7) The Temp vs. Age and k_t vs. Age plot for the given data:** These plot give the idea of the temperature and k_t variation for which the Maturity and strength will be calculated
- 8) Other Screens:** Besides this there are various warning and limit selecting screens to decide the limits applied to the data according to user judgment.

4.4 A Step by Step Guide to Using the RoD Software

This section explains the detailed step by step procedure to operate the RoD software. It maintains the usual flow of the software and explains the steps that the user might come across while using the software.

4.4.1 System Requirements

The user needs to have an optimum performance machine with a CD Drive installed and Windows 95 or above operating system.

4.4.2 Installing software

Double click on the “SETUP.EXE” file provided in the supplied installing CD-ROM. The install wizard will guide through the installing instructions and will install the software in the location specified by user.

4.4.3 Using the Software

4.4.3.1 Step 1: Double click on the “RCPD.EXE” file in the location specified during installation of the software. The program will start with the introduction screen as shown in Figure 2.

4.4.3.2 Step 2: After a two second delay, the main menu screen (shown in Figure 4.1) will appear which will guide the user throughout the operation. The first screen over the main menu would be the disclaimer (Figure 4.3) as shown below:

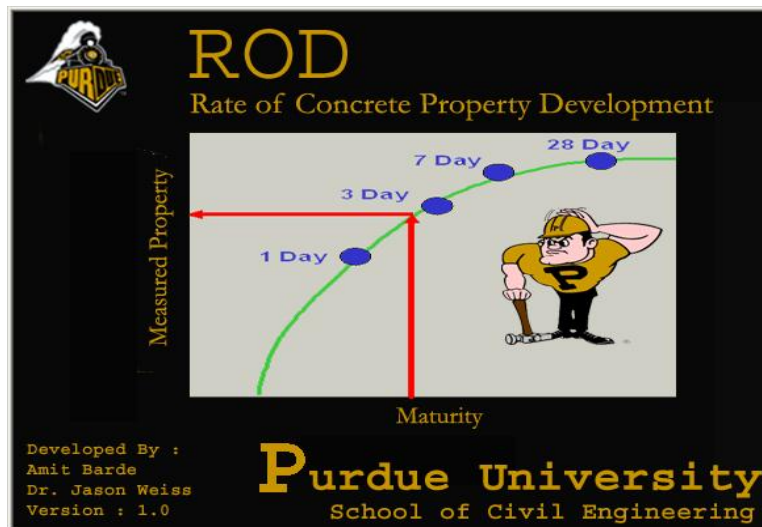


Figure 4.2 Title Screen

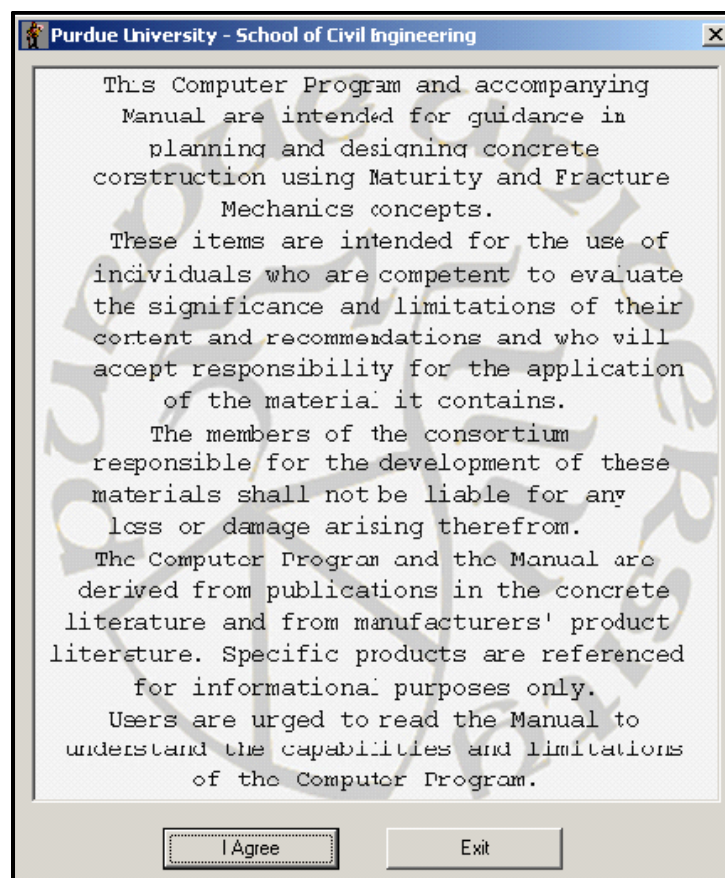


Figure 4.3 Disclaimer Screen

To work with the software, the user needs to accept the terms and conditions mentioned in the agreement. If the user agrees to the terms and conditions, he/she may continue by clicking the “I AGREE” button. He/she may exit the program by clicking “EXIT” button.

4.4.3.3 Step 3:: After clicking the “I AGREE” button, the software will show the Unit Screen as shown in Figure 4.4

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Please specify the following information.

Mix Identity

Identity No. : Comments:

Measured Property :

Name : Unit :

Constants :

Activation Energy (E) : J / mol

Gas Constant (R) : J / (mol K)

Time : Maturity :

Unit : Unit :

Reference Temperature :

Temperature : Unit :

Help Ok Exit

Figure 4.4 Information Screen.

There are five main section in this screen:

- 1) **Mix Identity:** User can provide the information about the Mixture he/she is testing in the Mix Identity Section. The “Identity No.” and the “Comments”

will appear on all of the graphs throughout the calculation enabling the user to avoid any confusion while working with different mixture proportions.

- 2) **Measured Property:** User can specify the name of the property he/she intends to work with and its unit here. For convenience the information in “Name” and “Unit” field will be automatically used in the rest of the calculation part of the program. By default the property will be “*Strength*” and the unit will be “*psi*”
- 3) **Units:** User will specify the units for Time and Maturity here. These units will be used throughout the program. For the current version, the user will not have the option to change these values provided. By default these values will be set for “*day*” as shown in Fig. 3.
- 4) **Constants:** User will provide the value of Activation Energy (E) that he/she desires to be used for the calculations. This value will remain constant throughout the program. The value for Gas Constant (R) is for information only and won't be accessible to the user to change. The Gas Constant used throughout the calculations is 8.314 J/(mole*K). The unit of the activation energy and gas constant R will be “J/mole” and J/(mole*K) respectively throughout and user will not have any option to change it. By default the activation energy will be set to 40000 J/mole with an option to change.
- 5) **Reference Temperature:** For current version of the software the User can not change the reference temperature or its units. By default the Temperature will be set to “23” and the unit to “Degree Celsius”

After specifying the required information the user may proceed with the “Ok” button. At any stage the user can exit the program by clicking the “Exit” button. The user can find this information on the computer by clicking the “Help” button.

4.4.3.4 Step 4 – Data Input: The user will be guided to the “Choice of Data Source Screen” by clicking “Ok” button in the Units Screen. This screen will look like as shown the image shown in figure 5. The first option “Data Input from a “*.TXT” or “*.DAT” file” allows user to browse through the computer and select a .TXT or .DAT file already stored in the computer. While the second option will allow the user to manually input data as described later in this section.

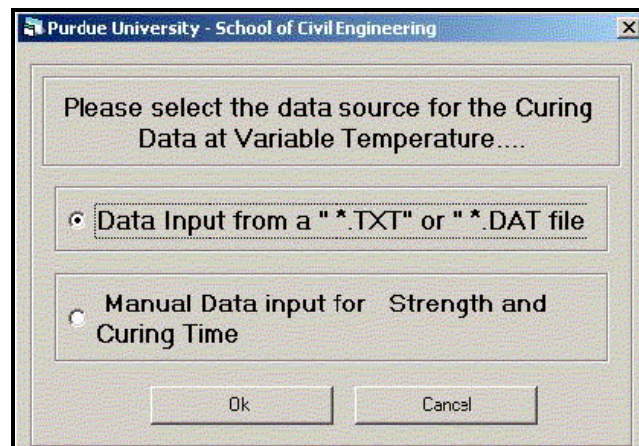


Fig 4.5 Data Source

To import data source files from a text file the file should follow the following guidelines. An illustration of this data is shown in Figure 4.6.

1. It should be *.TXT / *.DAT / *.CSV format only.
2. It must consist of two columns (No more/No less) with a comma separating each column.

3. The first column of the data file in this form will be recorded as the age in days and the second as the measured desired property (i.e. desired property measured for the laboratory cured specimens at reference temperature.)
4. Files with columns separated by TABS will not work.
5. The first line of the file would be the details about the mix design and comments. This line must be added in the file. If not, the first data reading will not be considered in calculations, thus leading to an undetected error. The sample file will be as shown below:

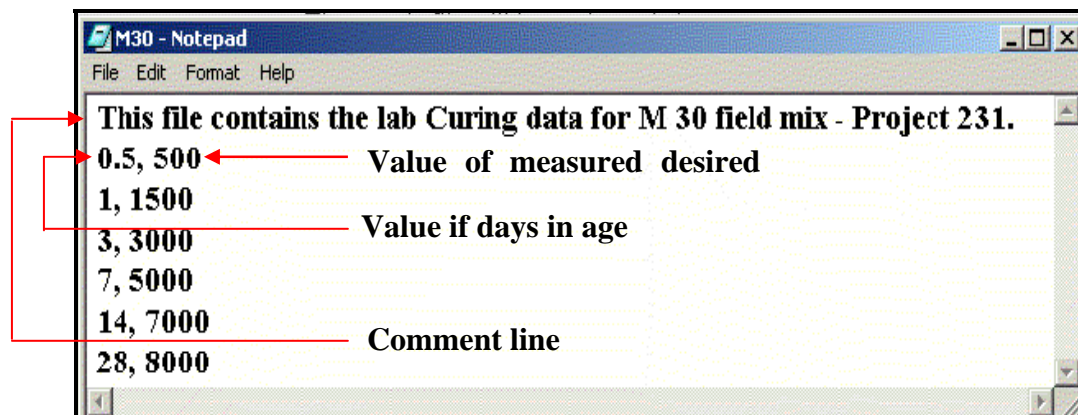


Fig 4.6: Text File Format

The user can then select the required file and click “Ok” button to proceed. If the data transfer is successful, the screen shown in Figure 4.7 will appear. User can click plot to proceed to Step 5, which is explained in the following section.



Fig 4.7 A Screen that Appears When a Text Data File Has Been Imported

The second option “Manual Data Input for Desired Property and Curing time” allows the user to input the required laboratory curing data manually. If the user selects this option, the Manual Data Input screen will appear as shown in Figure 4.8.

In the manual form the user can input the relevant data in the form that is provided. User should ensure that the “Input total number of Data Sets,” marked by arrow 2, has been correctly input, otherwise leading to errors in calculations. It should be noted that if the user needs to input more than 10 fields to input the data manually, the can simply enter data and click on the next file. The maximum allowable size for manual data input in the current version is 50.

The software enables and recommends the user to save the manually entered data in a *.TXT format so that the same data can be used for further calculations, thereby avoiding the tedious job of inputting the data manually each time. By clicking the “SAVE” button, the program automatically saves the data into the compatible format. If the user decides to save the data by clicking the “SAVE” button, the screen shown in Figure 4.9 appears.

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Input total number of Data Sets: 5

Time(Days) Property (\$)

1	1500
3	3000
7	5000
14	6000
28	8000

Exit Save Plot Next >>

Figure 4.8 Manual Data Input

Save As

Save in: New Folder

History
Desktop
My Documents
My Computer
My Network P...

File name: data

Save as type: Text Files (*.txt)

Save Cancel

Figure 4.9 Data Save Screen

The user can browse through the computer for an existing file or can create an altogether new file, which can be read by the software in the future. If the user doesn't click on the "SAVE" button and accidentally goes for plotting by clicking the "PLOT" button, the software will give a recommendation to save the data, as shown in Figure 4.10:



Figure 4.10 Save Data Warning Screen

If the user still doesn't want to save the data, clicking the "IGNORE" button will tell the software to proceed with Step 5.

4.4.3.5 Step 5 Determination of the Value of Long-Term Strength, S_{∞} - The user will get a graph the desired property (S) versus $1/\text{Time}$ plotted for all of the data entries that user entered, either manually or using a file. The form will look like that shown in Figure 4.11. This plot is used to determine the value of S_{∞} . The program performs a linear regression analysis over the data and plots the resulting straight line. The y-intercept of the straight line is calculated as S_{∞} . The value of S_{∞} is generally determined using only data from specimens tested at later ages. The user can decide the limit for this data by choosing an x-axis so that only the values less than that limit (since the x axis is one over time a later age corresponds with a lower value on the x axis) will be considered while plotting and performing the linear regression analysis.

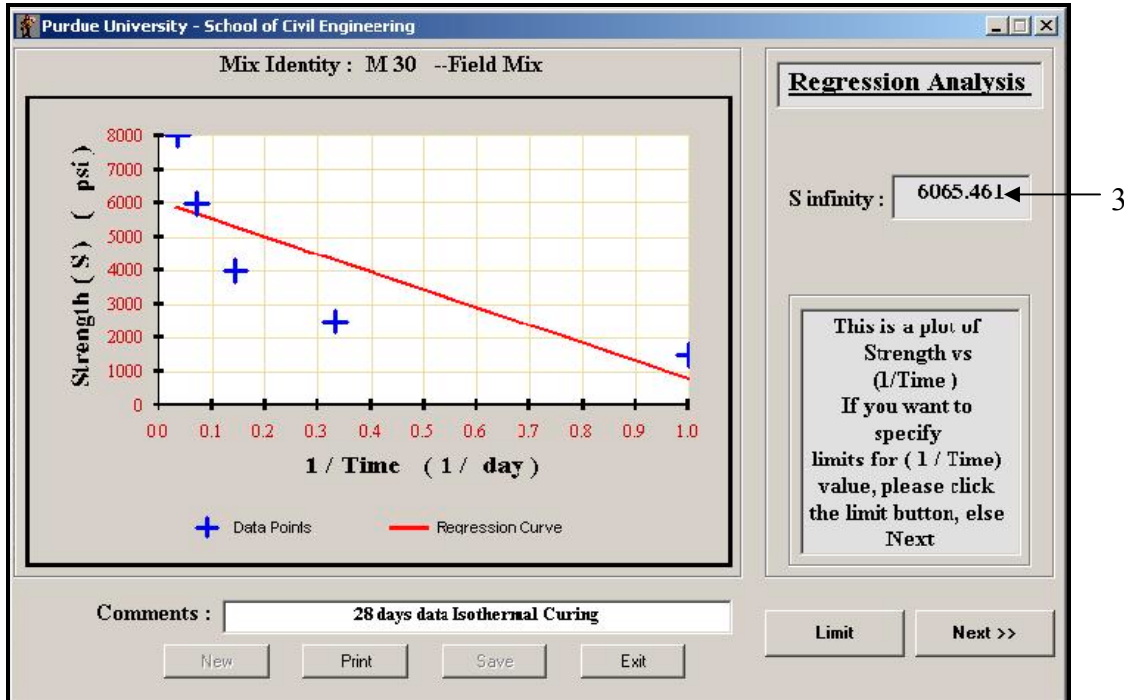


Figure 4.11 Plot of S vs. (1/Time)

The following example will be used to illustrate this concept more clearly and to more clearly illustrate the procedure for deciding the limit. Consider the data shown in Figure 4.11. It shows data for Strength plotted at 28, 14, 7, 3 and 1 days respectively. For this data the S_{∞} is calculated as 6065.461 psi, shown by arrow 3, but the Strength value at 28 days was measured directly to be 8000 psi. This shows that the value obtained from the software for S_{∞} using all the data (6065.61) is not a correct estimate. To improve the value of the estimate the user needs to consider only the later age values. This can be achieved by clicking “ Limit ” button. The limit screen will pop up as shown below:

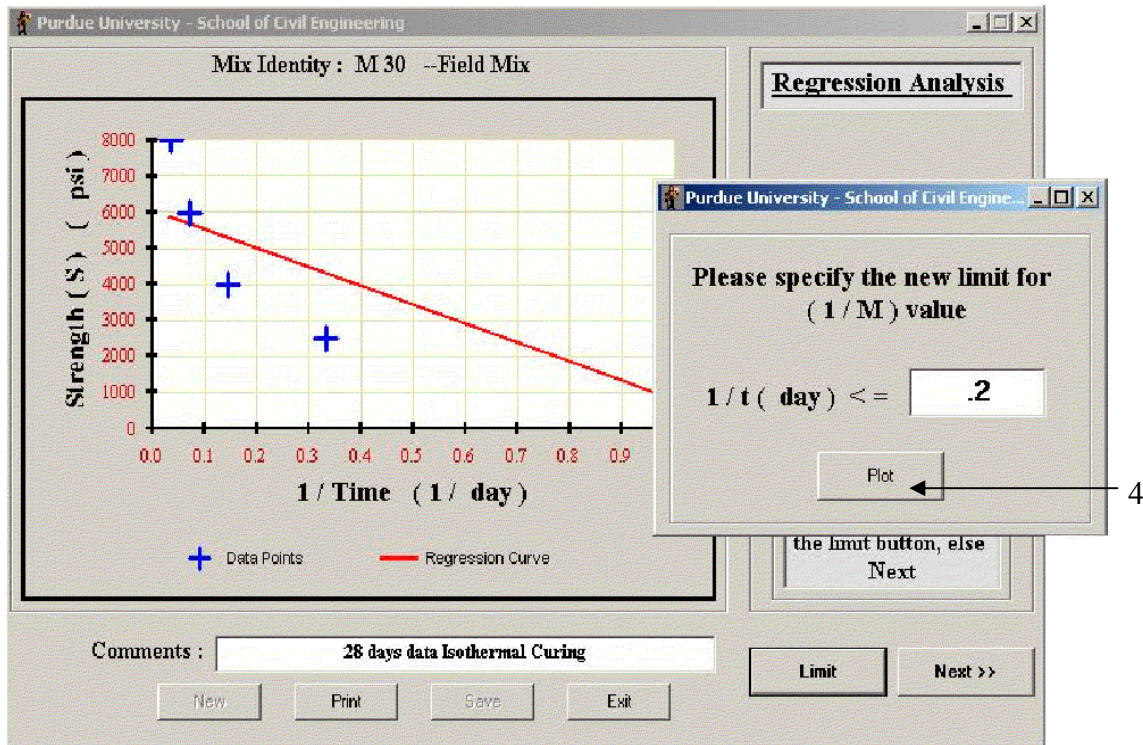


Figure 4.12 Limit Screen Pop Up

If user wants to consider only 28, 14 and 7 days data for calculating the S_{∞} , the good choice for the limit would be 0.2 on x-axis. Only points that are less than 0.2 will be considered, that means the data points corresponding to 28, 14 and 7 days will be considered. Thus, if the user proceeds with the limit as 0.2 by clicking “PLOT” button on the Pop up screen, shown by arrow 4, the new plot will be as shown in Figure 4.13.

The plot considers data points for 28, 14 and 7 days only, giving S_{∞} value as 9000 psi, which would be a better estimate. If the user is still not happy with the estimate of S_{∞} , he/she can choose a different limit until the program gives a reasonable estimate for S_{∞} . Once the S_{∞} value has been finalized, the user can proceed further by clicking the “Next >>” button.

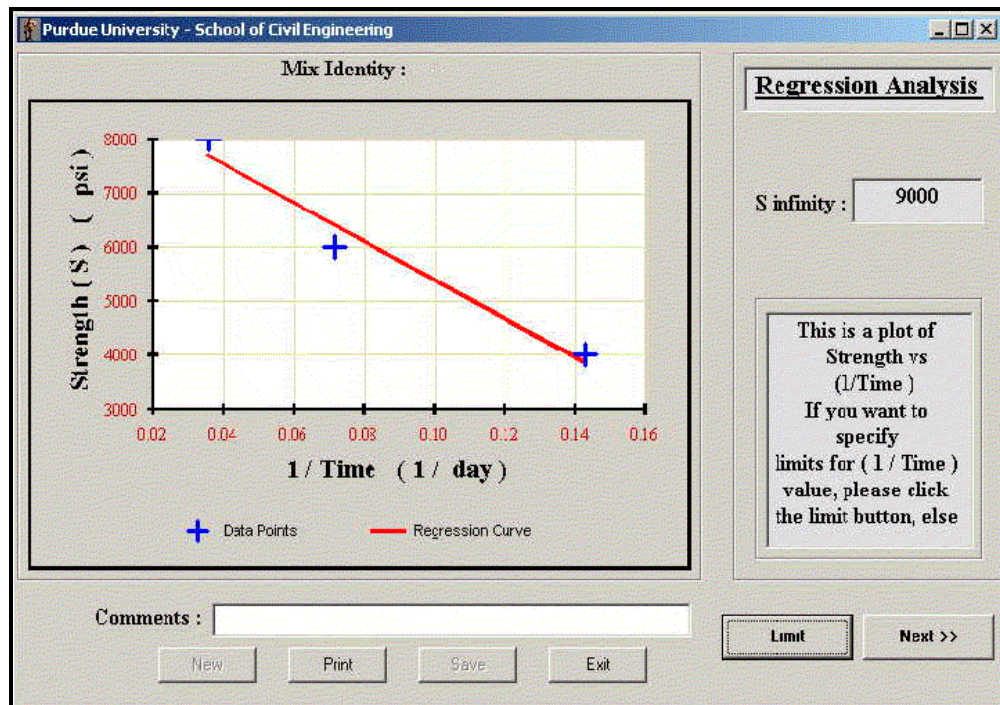


Figure 4.13 Plot of S vs. (1/Time) with limit

4.4.3.6 Step 6 : Plot of $S/(S_{\infty} - S)$ vs. Time to Determine the Offset Maturity - The plot shown in Figure 4.14 can be used to determine the values of the offset Maturity (M_0 , the maturity at which the desired property begins to develop) and the value of the rate constant at reference temperature (k_r). To have a correct estimate of these constants early age data should be primarily considered. Thus, the steps employed are very similar to those used in finding S_{∞} . The user can choose the limits the same way he/she chose for S_{∞} . Once satisfied, the user can proceed further by clicking the “Next >>” button.

It is quite possible that the value of M_0 obtained from one of the fits may be negative for particular data ranges, however it should be noted that a negative M_0 has no physical significance. So in such condition the program flashes a warning screen (Figure 4:15)

that the value of M_0 is being calculated as negative. It allows the user to change the limits over which the data is fit accordingly. If the user decides to proceed further with the negative value, the value of M_0 is automatically set equal to zero for further calculations.

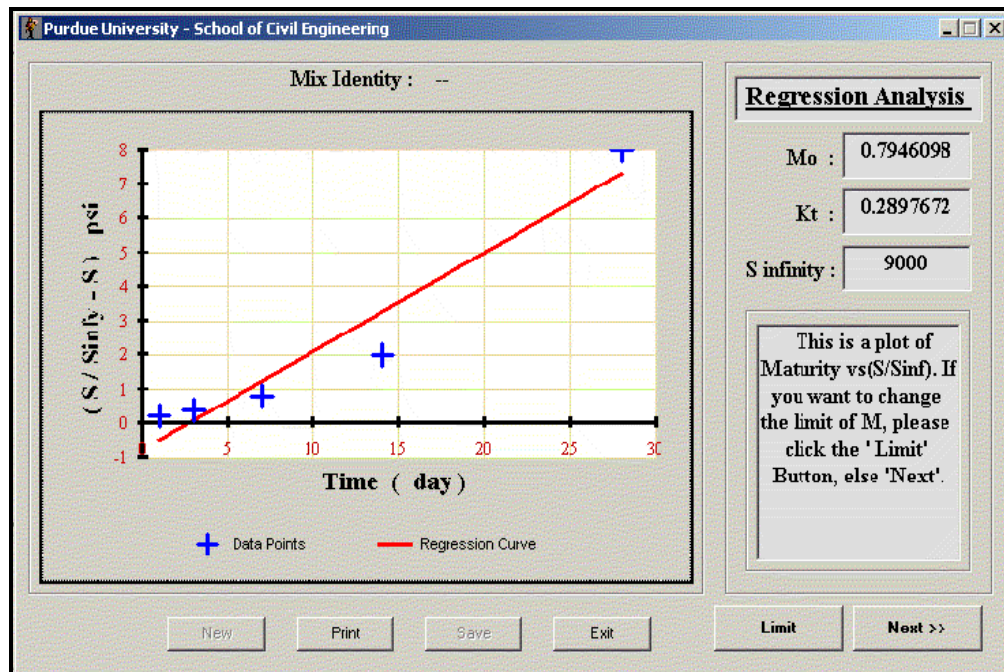


Figure 4.14 Plot of $S/(S_{\infty} - S)$ vs. Time

4.4.3.7 Step 7 – Master Curve- The master curve describes the relation between desired property and maturity. Since the three constants have been determined the master curve can now be developed. Figure 4. 16 illustrates a plot of the property versus maturity Master curve for one set of materials.

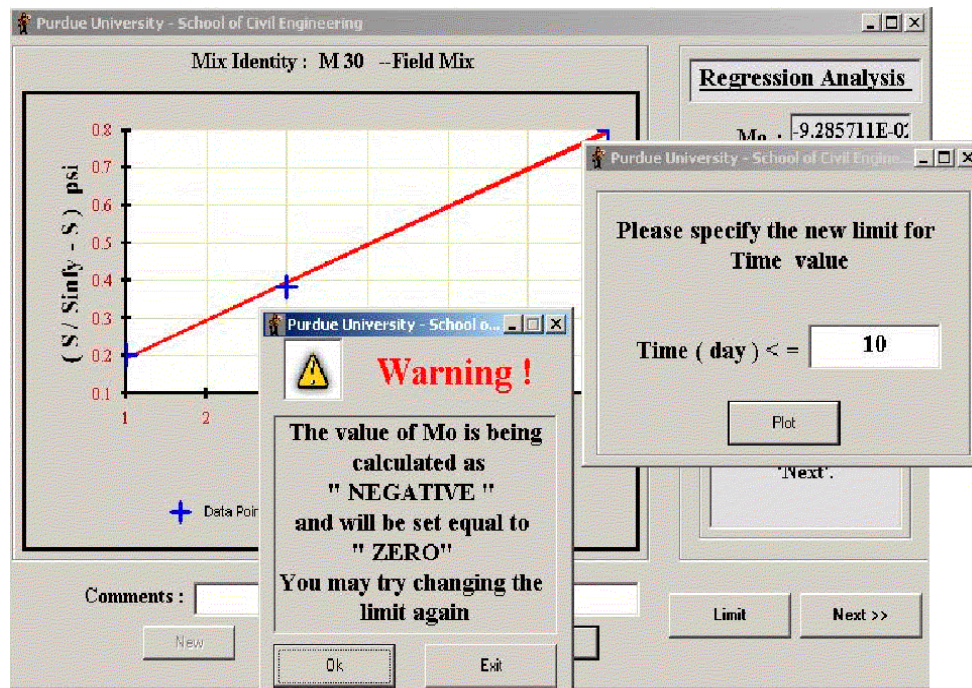
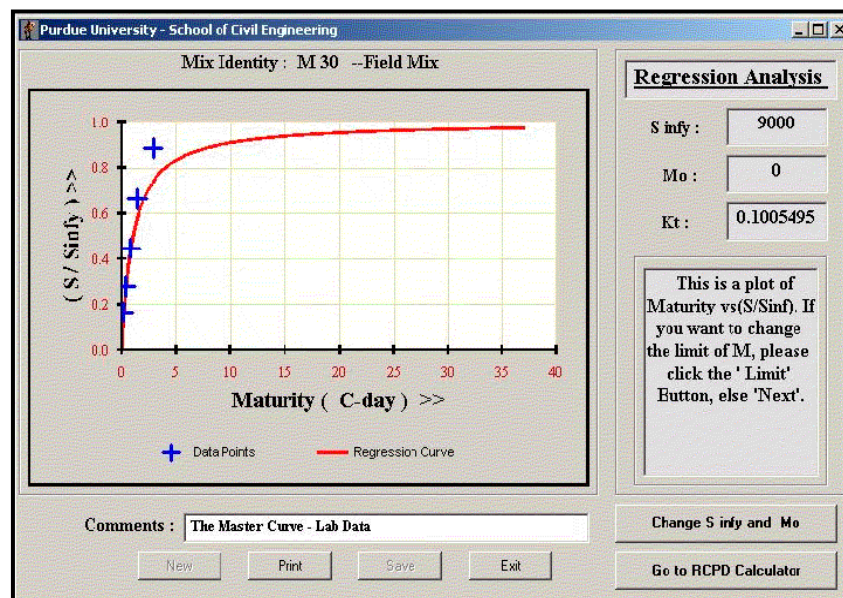
Figure 4.15 Warning Screen for Negative M_0 values

Figure 4.16 Master Curve

It should be noted that if the user is not satisfied with the fit of the master curve, they can go back and start right from the beginning, deciding new values for each of the constants. This can be achieved by clicking the “Change S_{∞} and M_0 ” button. Otherwise the user may proceed further by clicking “Go to RCPD Calculator” button.

It should be noted that in each of the graph screens, the user has the option to have a print out of the form for his/her record. Clicking the “PRINT” button will print the corresponding form on the default system printer. Current version does not option to save the forms. Also, the user may terminate the program at any stage by clicking the “Exit” button placed at various locations.

4.4.3.8 Step 8: RCPD Calculator: This is the second part of program. It deals with the calculation of Maturity for a given time-temperature history and predicts the corresponding desired property, or vice-versa. When the user clicks the “Go to RCPD Calculator” button, and Figure 4.17 will be displayed.

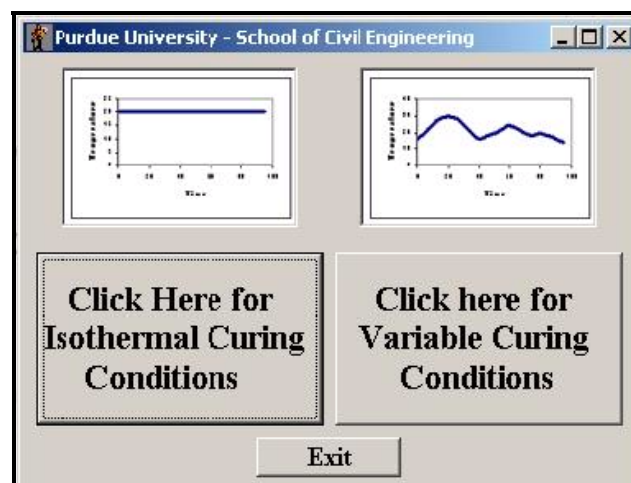


Figure 4.17 Choice for Curing Conditions

For prediction of the desired property for specimens cured under laboratory conditions at the reference temperature, the user can click “Click here for Constant Temperature Curing Conditions” button. The RCPD Calculator Screen will be flashed.

Figure 4.18 RCPD Calculator

The user needs to select either the strength or maturity to be calculated and the software can then predict the other term by plugging in the know value and clicking the “COMPUTE” button.

By clicking “Field Data” the user can go to the next step to download the age and temperature data at variable curing conditions for further calculations. Clicking “Field Data” is as good as clicking the “Click here for variable temperature curing” button that appeared on the last form as it allows the user to select the source for the variable temperature curing data.

This option directly leads to the data download screen for variable curing condition data obtained from a data file. This option is used to find the Maturity of the field specimens and eventually calculate the strength using the Master Curve. Figure 4.19 will appear if the user selects to download data.

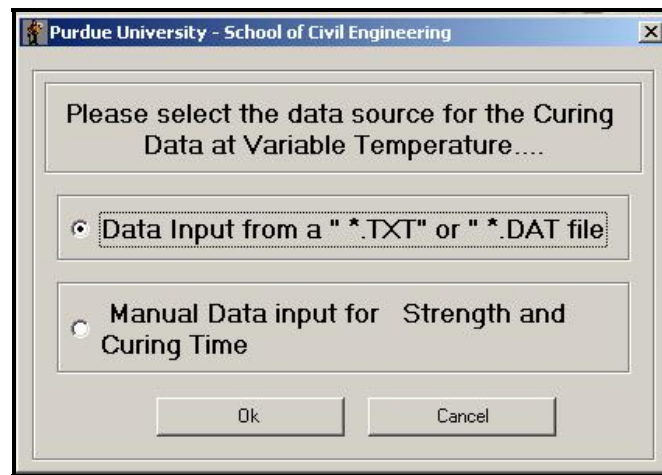


Figure 4.19 Data Download for Variable Curing

By clicking the “Calculate” button, the software will proceed to calculate the reaction rate for the input data, as well as the Maturity of the specimen, and end up with back calculating the desired property using the Master Curve developed in Step 7. The corresponding plots of Temperature vs. Curing Time and k_t vs. Curing Time will be displayed as shown in Figure 4.20, along with the Maturity and corresponding Property indicator screen. The software will not be able to predict the Strength Gain at later ages with the available curing age data for variable curing conditions. It will just calculate the Maturity and the Strength gain for the available curing data, however if the user would like to input an ‘anticipated temperature profile’ the maturity and material properties can be predicted.

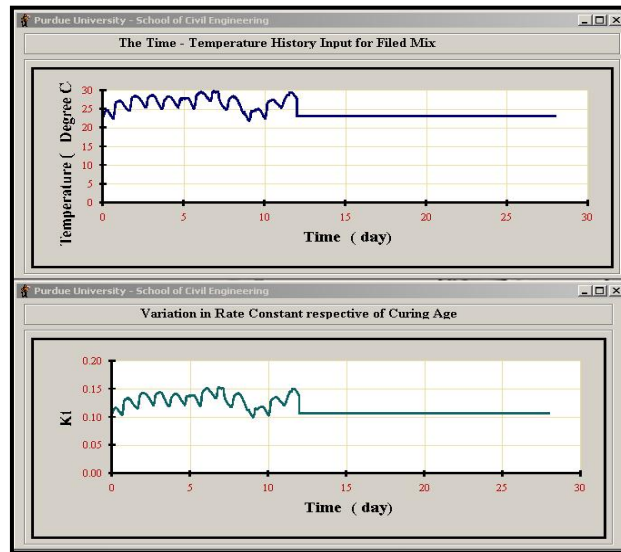


Figure 4.20 Various related plots for the Variable Curing Data

4.5 Conclusions

This chapter has described the background of the maturity method and has reviewed software used in the remainder of the study for computing the three main parameters used in computing the maturity property development relationships. It should be noted that the Arrhenius approach will be used in this study with a hyperbolic property-maturity relationship. Using this approach the complete property development curves can be determined using information on the long term strength (S_{∞}), the reaction rate (k_T), the offset or setting time (t_0) and the activation energy (E_A). Chapter 5 will present experimentally obtained information for each of these parameters for the repair materials investigated in this study.

CHAPTER 5: EXPERIMENTAL RESULTS

This chapter presents the results of the various experiments that were used to evaluate the performance of each of the rapid setting repair materials. The results are divided into three categories. The first category, described in Section 5.1, focuses on performing a materials characterization to determine the rate and magnitude of the mechanical properties that develop. The properties examined were compressive strength, flexural strength, static and dynamic elastic modulus, setting time, and temperature development. The second category, described in Section 5.2, focuses on evaluating the volumetric stability and early-age cracking potential of each of the twelve materials. These experiments included measurement of autogenous and drying shrinkage, as well as ring testing. The third category, illustrated in Section 5.3, describes the results of experiments designed to evaluate bond of the repair materials with a concrete substrate. These experiments focused on distinguishing between the tensile and shear bond strength with surfaces of different roughness in order to quantify the contribution of the bond as either a chemical or physical process. For a detailed description of the experimental procedures used the reader is referred to section 3.4.

5.1 Magnitude and Rate of Mechanical Property Development

The experimental program for characterizing the rate and magnitude of material property development for the repair materials consists of measurements of the time dependent compressive strength, flexural strength, elastic modulus, activation energy, setting time, temperature, and maturity. The following section describes each of these properties in greater detail.

5.1.1 Compressive Strength

Compressive strength tests were performed on 4" x 8" cylinders in accordance with ASTM C-39. Figure 5.1 illustrates the results of the compressive strength with each point representing the strength at 1, 2, 4, 8, 12, 24, 72, and 196 hours. It can be seen that the materials demonstrate a wide range of behaviors from the Base concrete which has a very high overall strength to materials like the EMACO and SP products which show a lower overall strength. For the most part however the majority of the specimens showed a 7 day (196 hour) strength of approximately 5000-7500 psi. It can also be observed that the rate of strength development varies from mixture to mixture (and depending on the type of binder used for each material). For example materials like DOTP, FX, HPC, PPF, Set45, Set45HW, SSRP, and THOROC reacted faster than the BASE while QRRR reacted at about the same speed and FX and SP reacted slower than the baseline case as illustrated by the shape of the curves.

5.1.2 Flexural Strength

Flexural strength tests were performed on 3"x3"x15" beams in accordance with ASTM C-78. Figure 5.2 illustrates the results of the flexural strength with each point representing the strength at 1, 2, 4, 8, 12, 24, 72, and 196 hours. It can be seen that the materials demonstrate a wide range of behaviors from the Base concrete which has a very high overall strength (1300 psi) to materials like the HPC, SET45, SET45HW, SP, and THOROC which showed strengths between 430 and 530 psi. The remainder of the materials (DOTP, EMACO, FX, PPF, QRRR, and SSRP) were observed to have long-term flexural strengths between 600 and 800 psi. The rate of strength development was similar to the rate of strength development shown by compressive strength measurements.

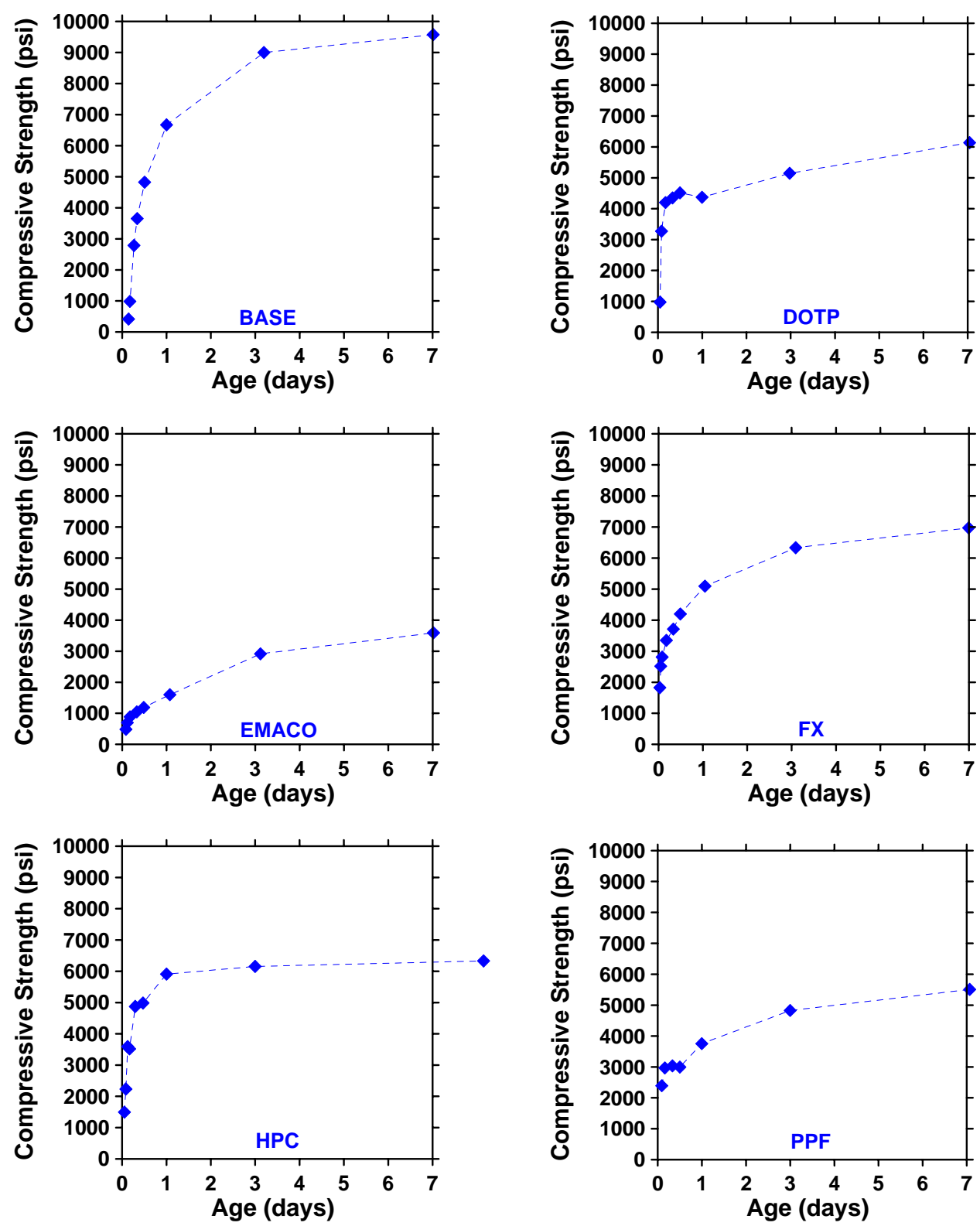


Figure 5.1: Compressive Strength Development as a Function of Time
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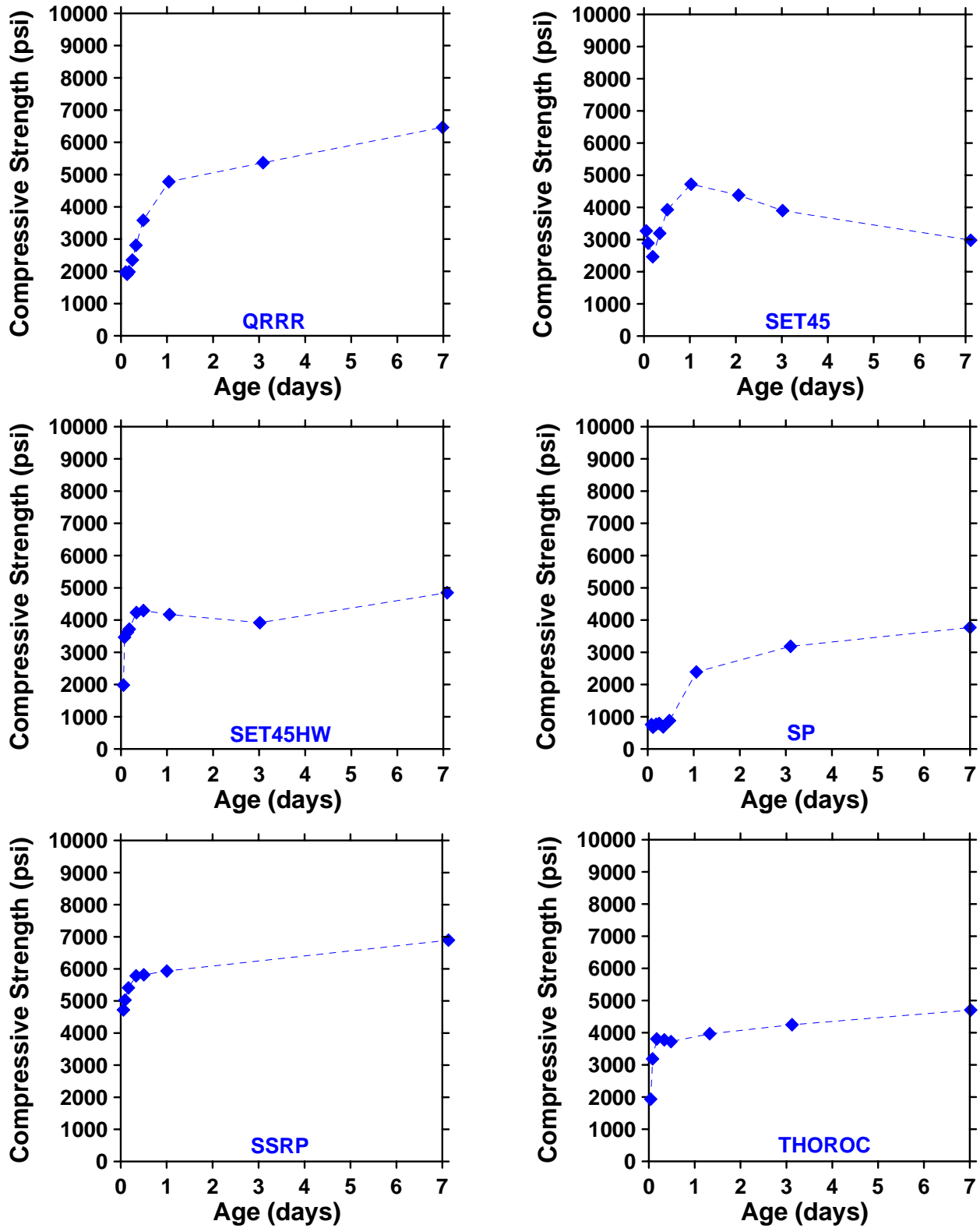


Figure 5.1: Compressive Strength Development as a Function of Time
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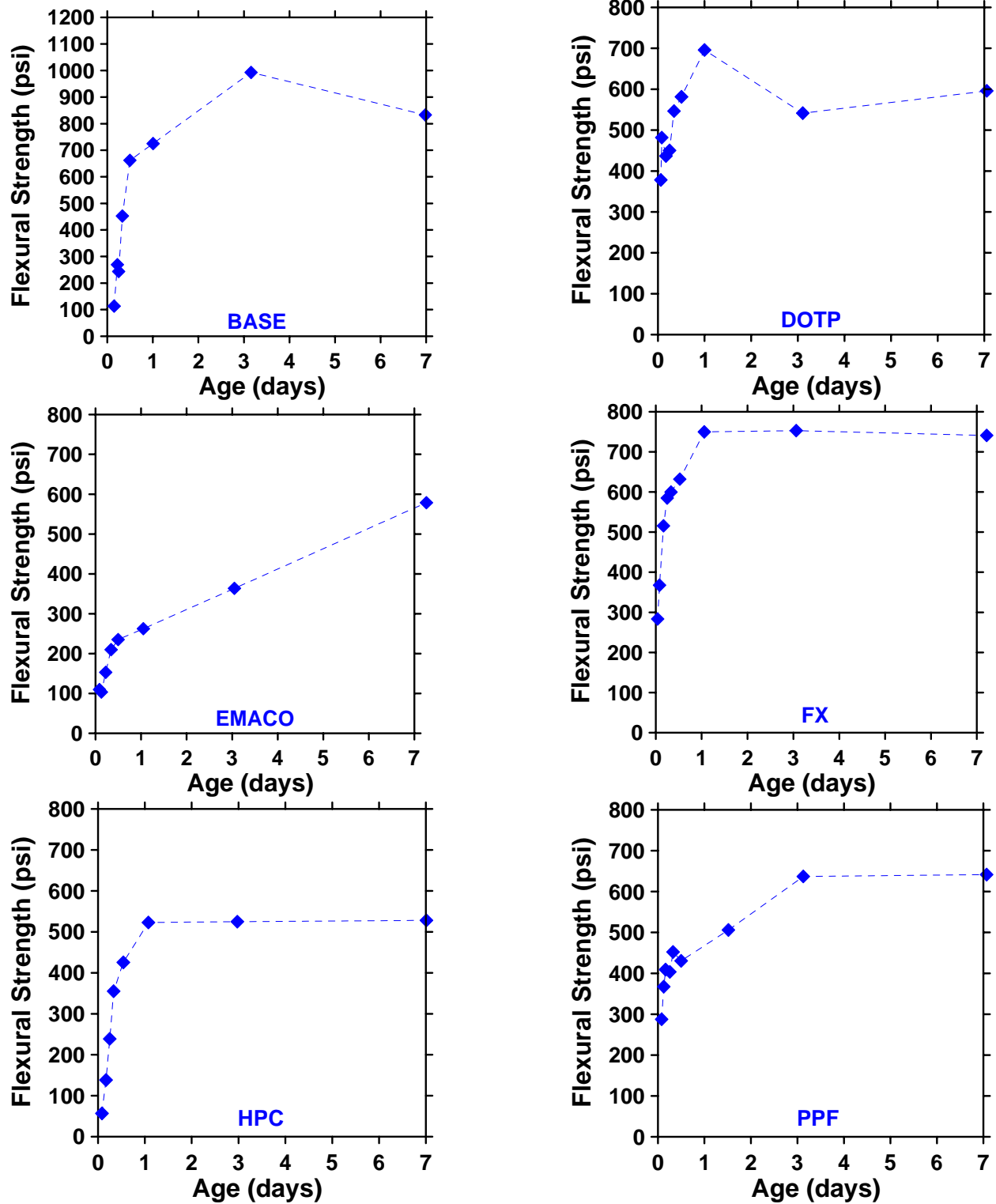


Figure 5.2: Flexural Strength Development as a Function of Time
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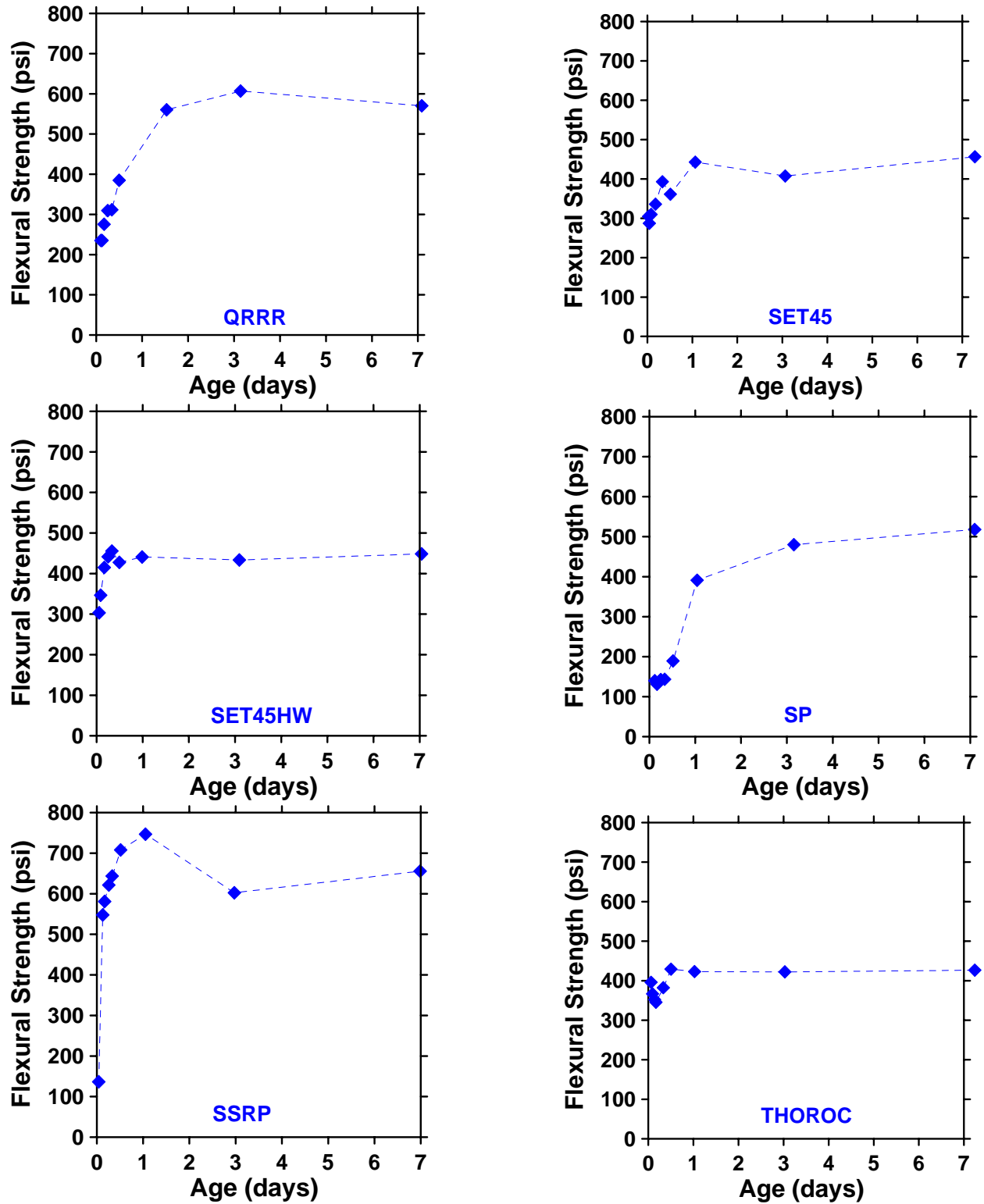


Figure 5.2: Flexural Strength Development as a Function of Time
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5.1.3 Static Elastic Modulus in Compression

Elastic Modulus tests were performed on 4" x 8" cylinders in accordance with ASTM C-469. Figure 5.3 illustrates the results of the flexural strength with each point representing the modulus at 1, 2, 4, 8, 12, 24, 72, and 196 hours. It can be seen that the materials demonstrate a wide range of behaviors from 3×10^6 psi to 5.5×10^6 psi with the BASE concrete showing a modulus of 4.8×10^6 psi. It should be noted that the only the SP material was substantially lower (3.0×10^6 psi) than the BASE and no materials were substantially higher than the BASE material. This indicates that the majority of these materials were within +/- 15% of those that would be expected for most concrete materials used in Indiana and should be quite compatible with concrete surrounding the repair. The rate of elastic modulus development was similar to the rate of strength development shown by compressive strength measurements.

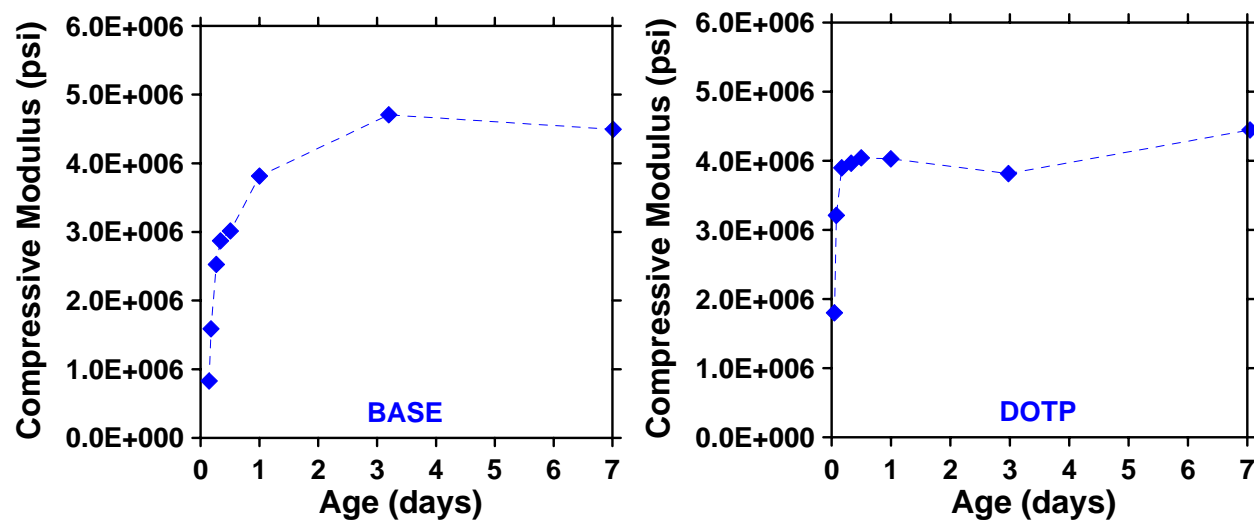


Figure 5.3: Elastic Modulus Development as a Function of Time
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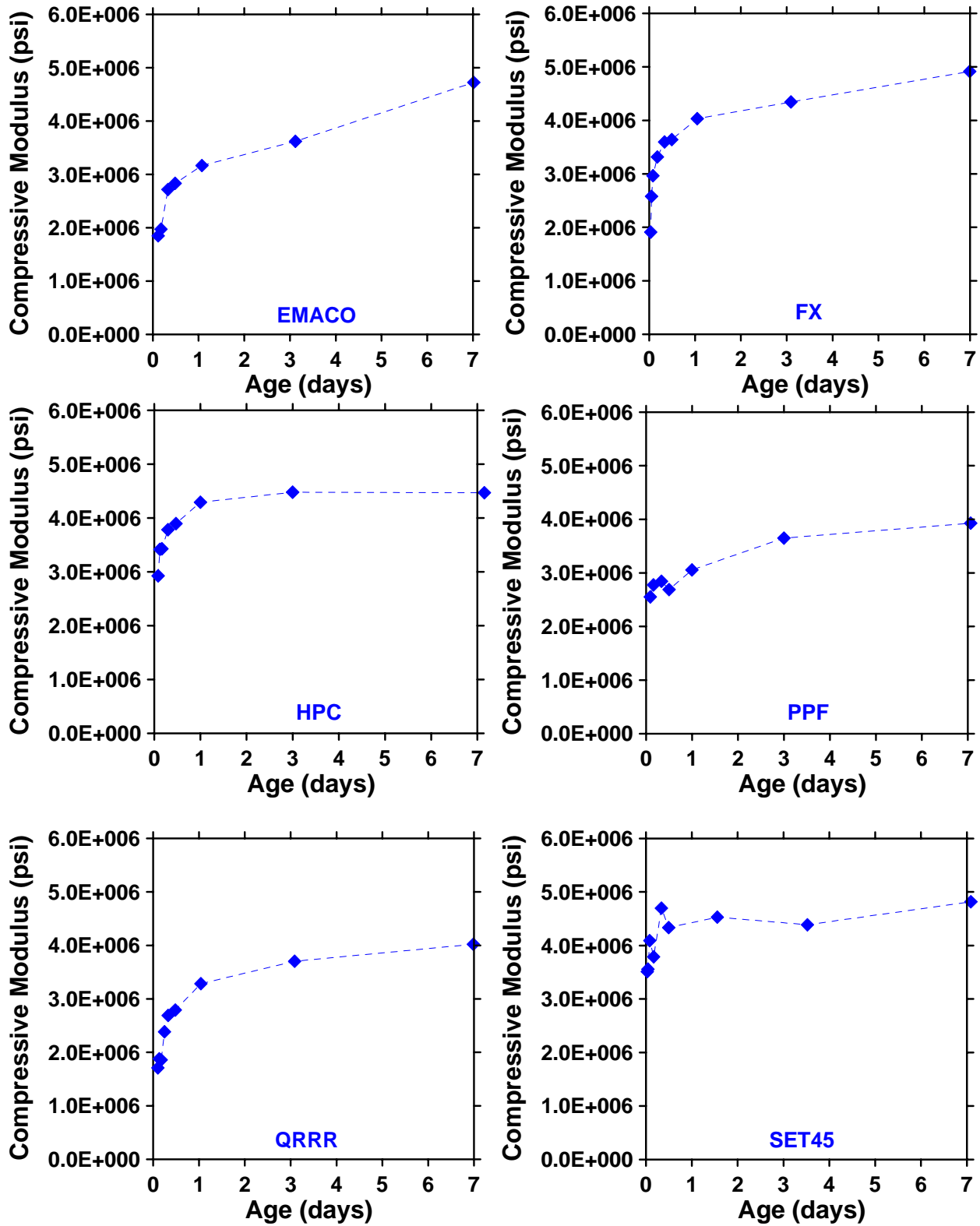


Figure 5.3: Elastic Modulus Development as a Function of Time
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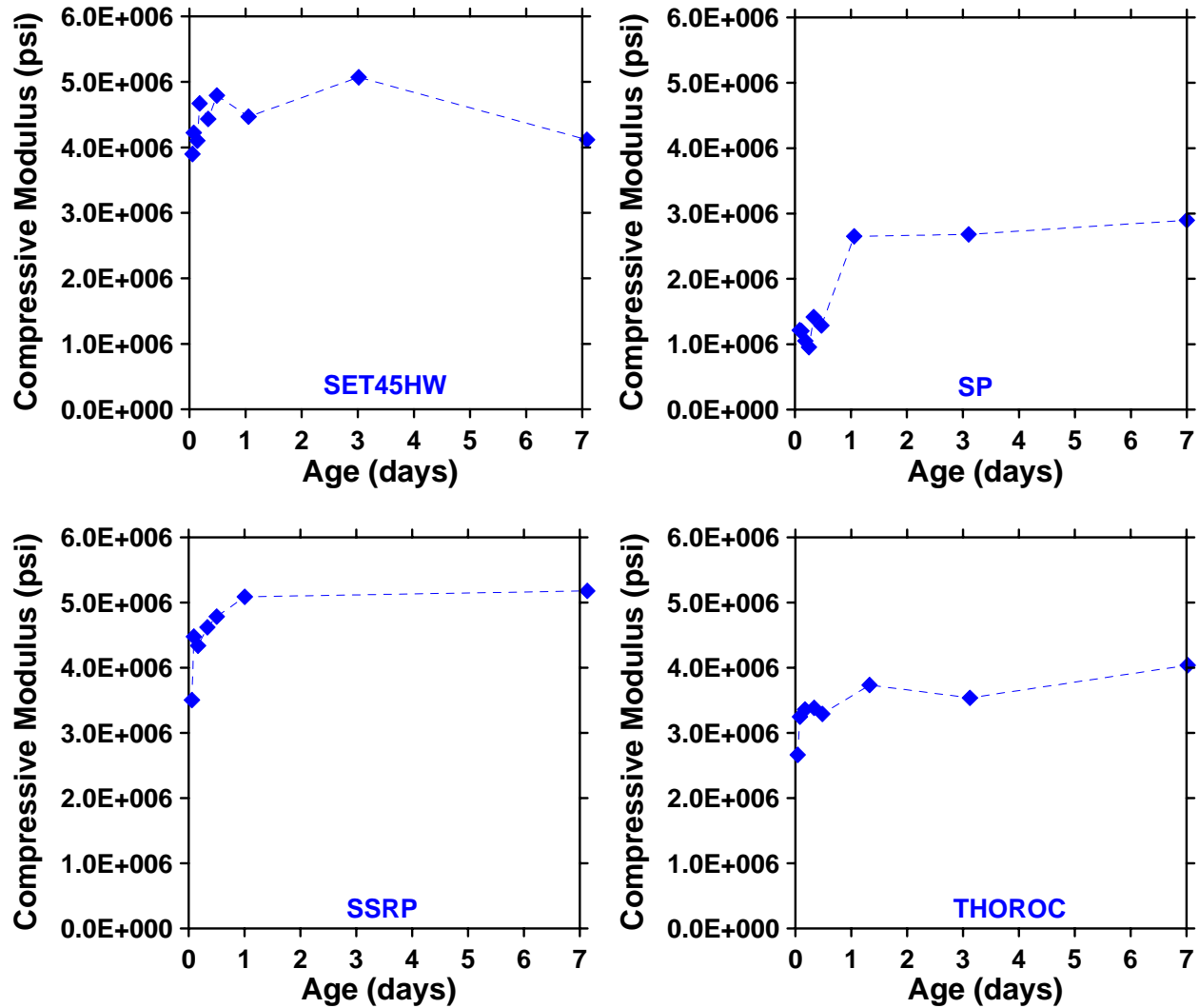


Figure 5.3: Elastic Modulus Development as a Function of Time
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5.1.4 Activation Energy

Figure 5.4 illustrates the activation energy for the materials examined in this investigation. The activation energy can be used to indicate the sensitivity of the material to strength development if the material is stored at different temperatures. Materials with a lower activation energy are less sensitive to temperature while materials with a higher activation energy are more sensitive to temperature.

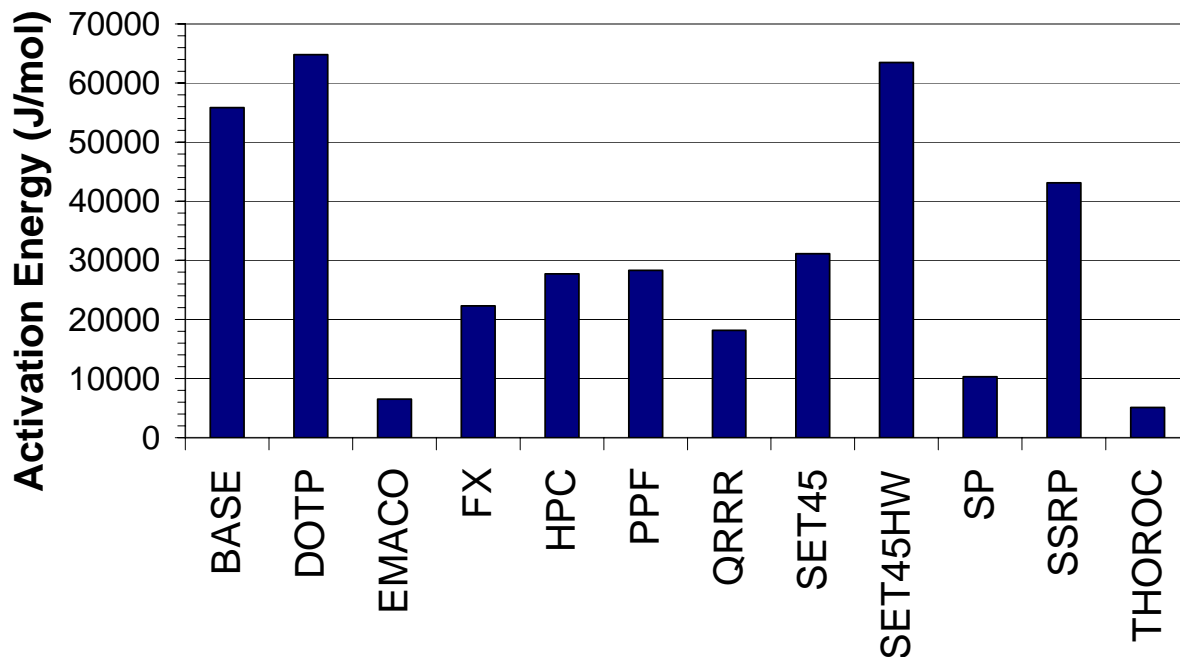


Figure 5.4: Activation Energy as Measured from Compressive Strength Cubes

5.1.5 Setting Time

Figure 5.5 illustrates the initial set time and final set time as measured using the Vicat test. It can be seen that the material response can be divided into three categories: a) materials setting in less than 15 minutes, b) materials setting between 15 minutes and one hour, and c) materials setting between 1 and 2 hours. The materials that set the fastest (less than 15 minutes) included FX, SET45 and SSRP, while the BASE, QRRR, and SP all took between 1 and 2 hours to set. The remainder of the materials set between 25 and 50 minutes.

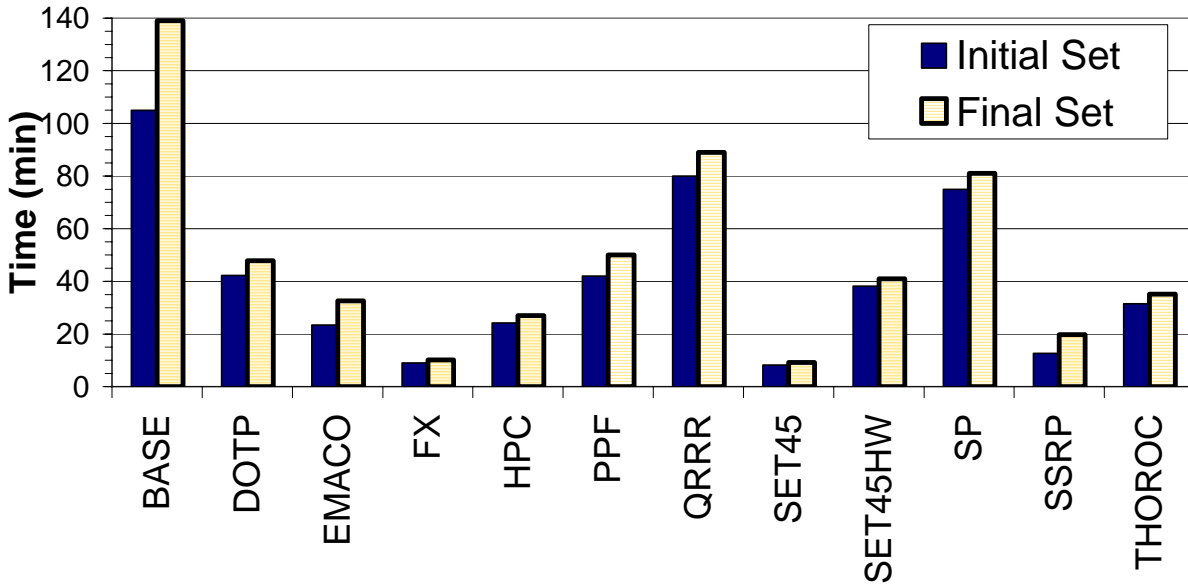


Figure 5.5: Setting Time as Measured from the Vicat Needle Test

5.1.6 Maturity Results

Figure 5.6 through Figure 5.12 illustrate the parameters obtained from using the maturity analysis of the data presented in Figures 5.1 through 5.5. The hyperbolic property development equation (the master curve model) described in chapter 4 should be recalled in viewing this data.

$$S = S_{\infty} \left(\frac{k_t(t-t_0)}{1 + k_t(t-t_0)} \right) \quad (5.1)$$

where three reference values, the long-term ultimate strength (or long term ultimate property) S_{∞} , the rate constant k_T , and the offset time t_0 (alternatively the offset maturity could be used as shown in Figure 5.6 which is essentially the product of the rate constant and t_0) can be used to compare the materials.

Figure 5.6 illustrates the offset maturity which can be thought of as the maturity at set time. It can be seen that the BASE material takes the longest to set while the FX and SET45 materials set the most rapidly.

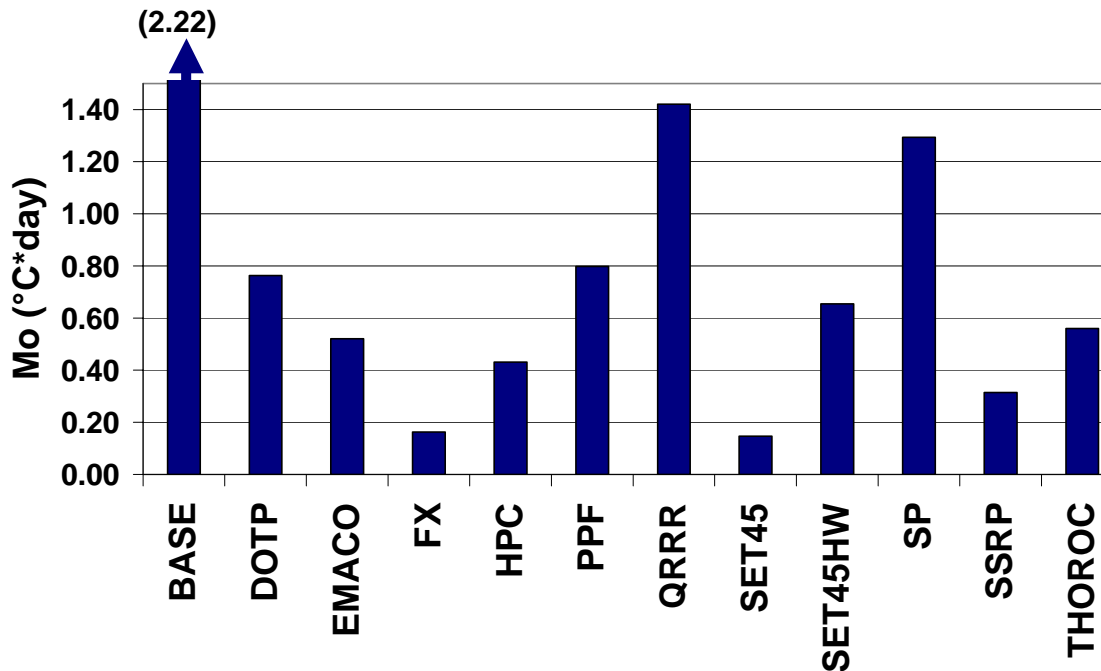


Figure 5.6: Offset Maturity as Predicted in the Maturity Method

Figure 5.7, 5.8, and 5.9 illustrate the long-term compressive strength, flexural strength, and compressive modulus respectively. The trends shown here correspond to the discussion from sections 5.1.1 to 5.1.3 of this chapter. Figure 5.10, 5.11, and 5.12 illustrate the rate constant for compressive strength, flexural strength, and compressive modulus development respectively. The trends shown here correspond to the discussion from sections 5.1.1 to 5.1.3 of this chapter. By using the information provided in these bar charts the complete time dependent response of the material can be obtained.

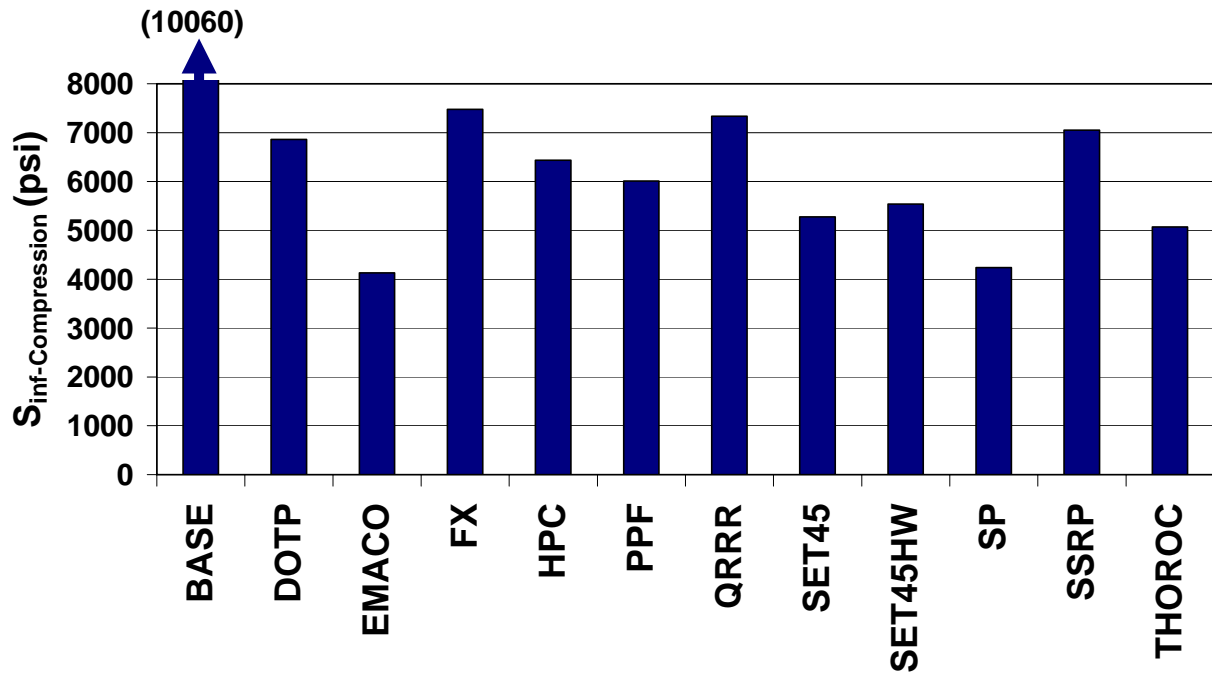


Figure 5.7 Long-Term Compressive Strength as Predicted Using the Maturity Method

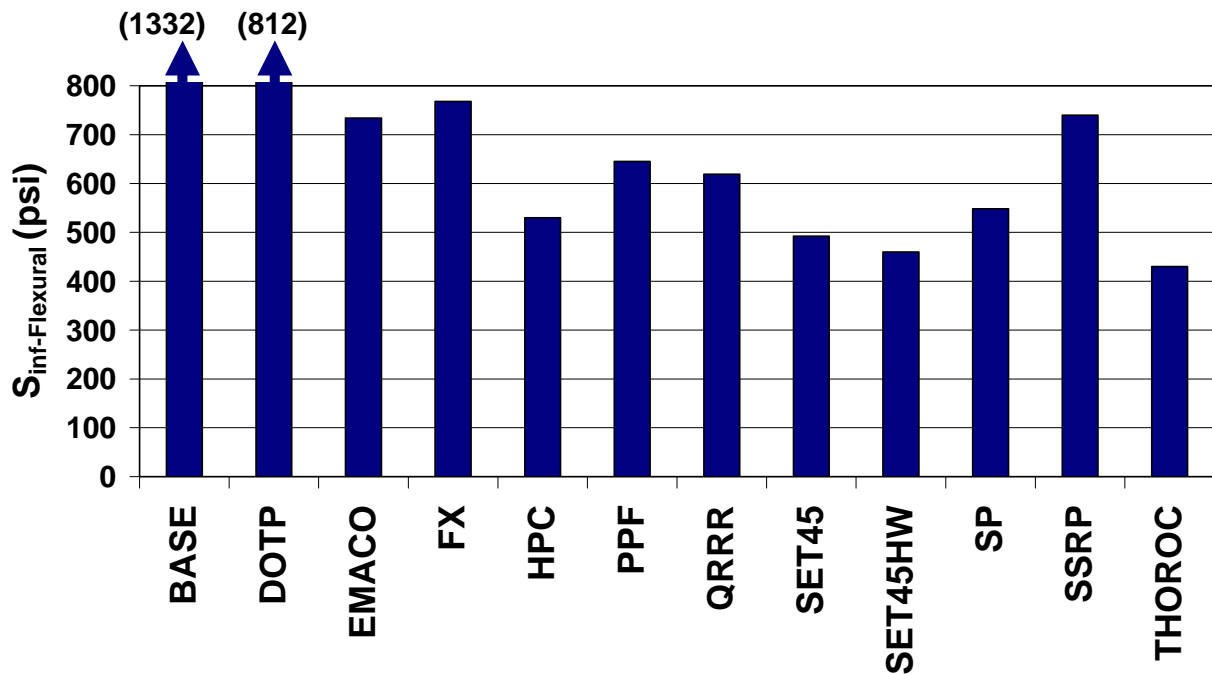


Figure 5.8 Long-Term Flexural Strength as Predicted Using the Maturity Method

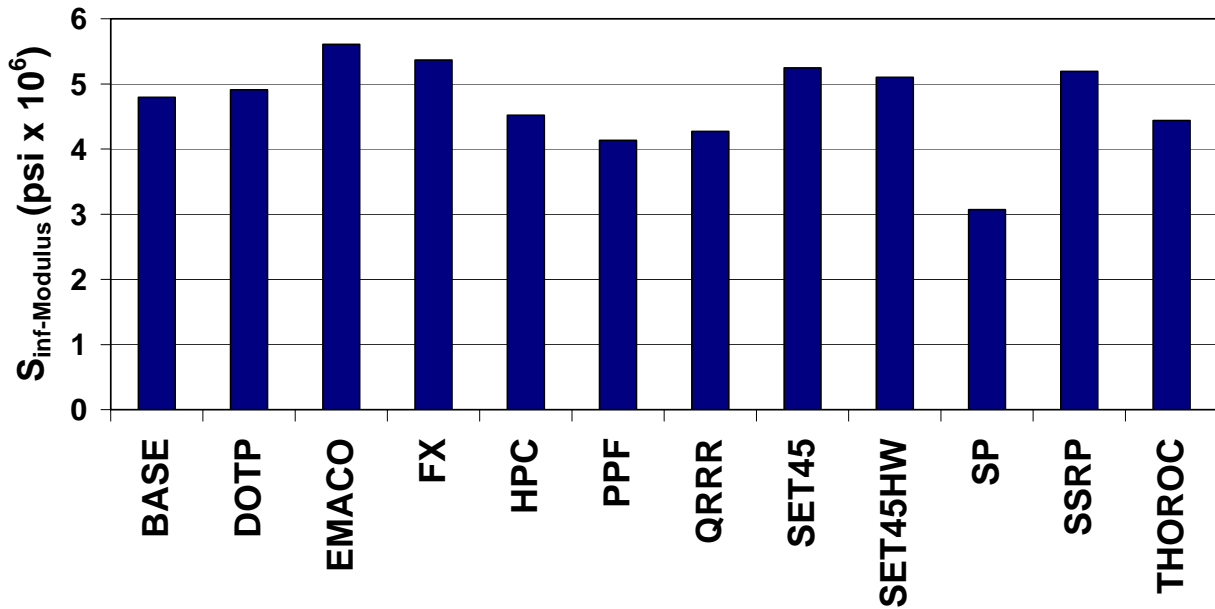


Figure 5.9 Long-Term Compressive Modulus as Predicted Using the Maturity Method

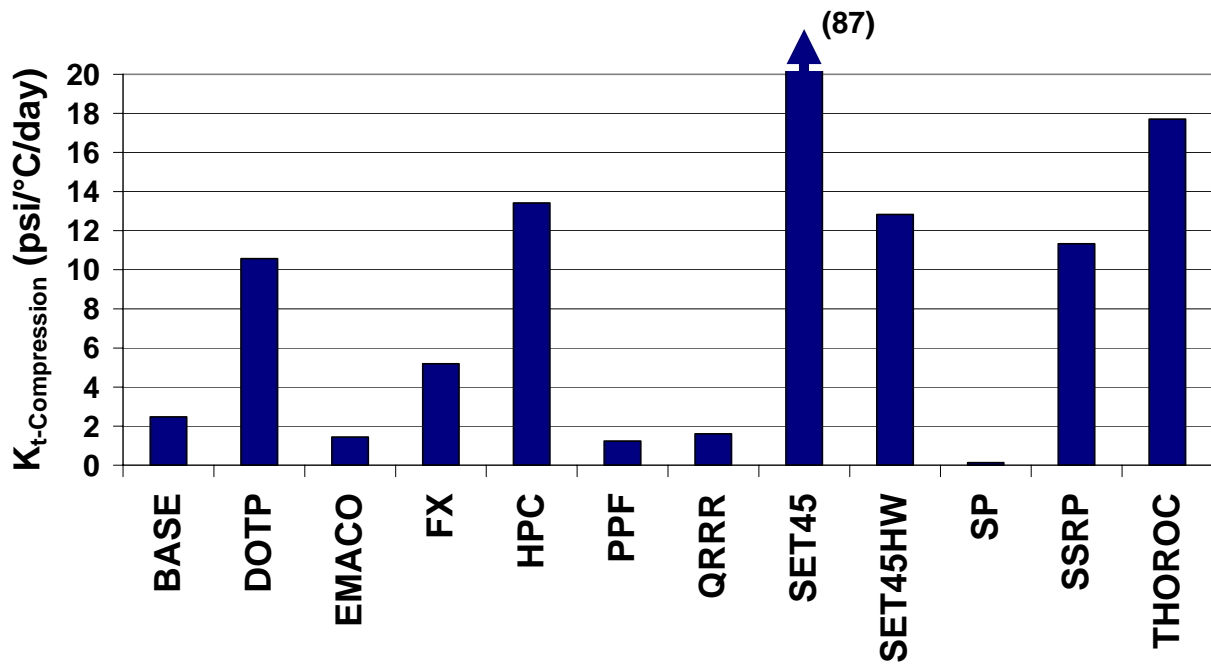


Figure 5.10 Compressive Strength Rate Constant Predicted Using the Maturity Method

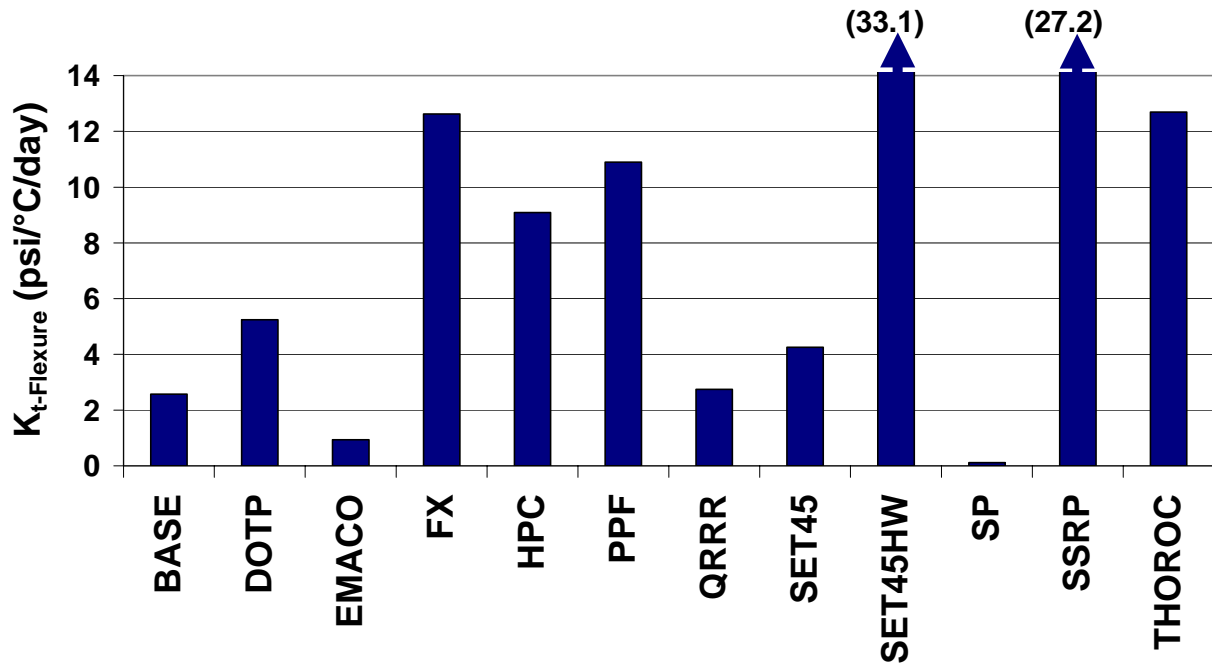


Figure 5.11 Flexural Strength Rate Constant Predicted Using the Maturity Method

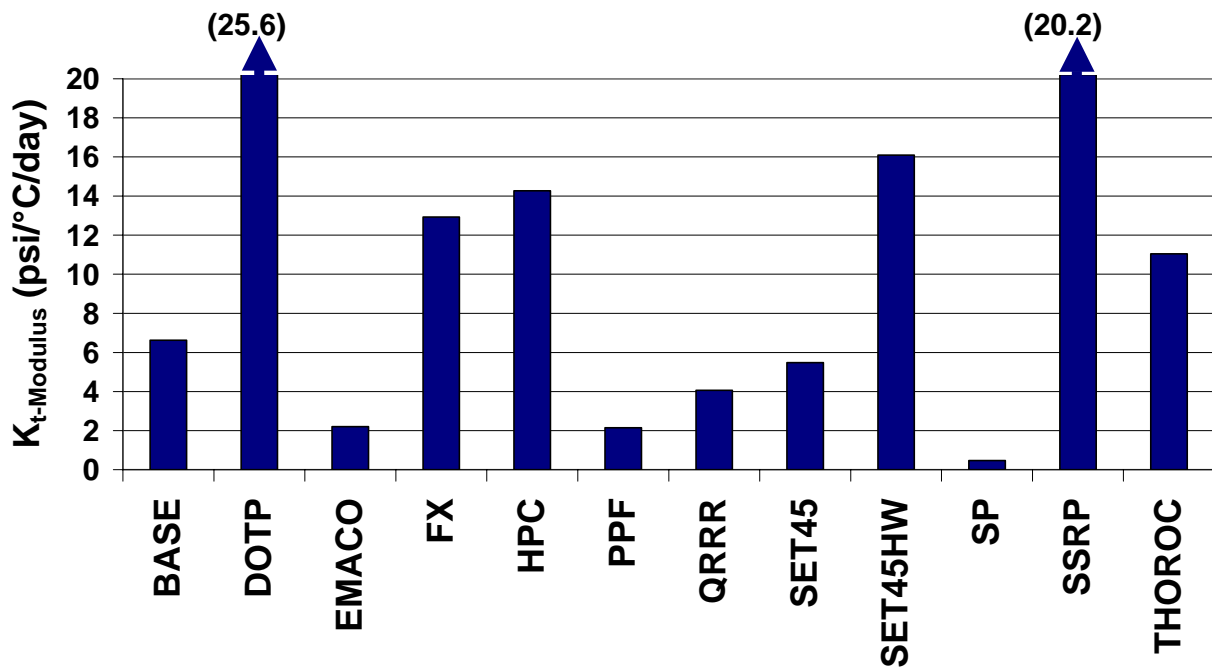


Figure 5.12 Compressive Modulus Rate Constant Predicted Using the Maturity Method

5.1.7 Temperature Measurement

Figure 5.13 illustrates the temperature that developed in a 3 “ x 3” x 15” specimen in the free shrinkage molds for use in correcting the early age shrinkage measurements. It can be seen that all of the materials showed some rise in temperature with a minimum rise of 8°C for the BASE case with a maximum of 45°C for the SET45 mixture. The temperature in the materials had typically returned to approximately room temperature after 8 hours.

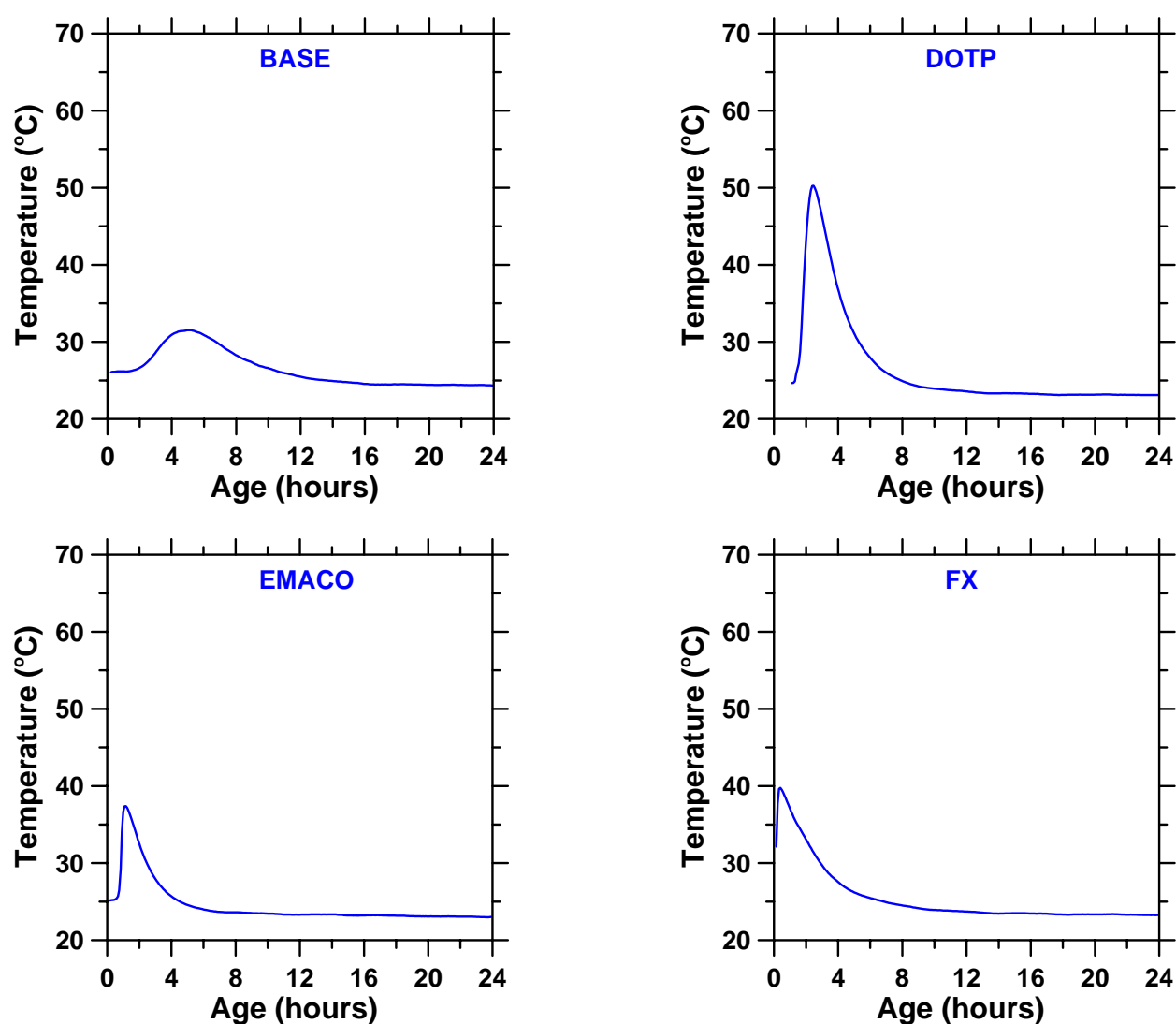


Figure 5.13 Temperature Rise in Rapid Repair Mortar Samples

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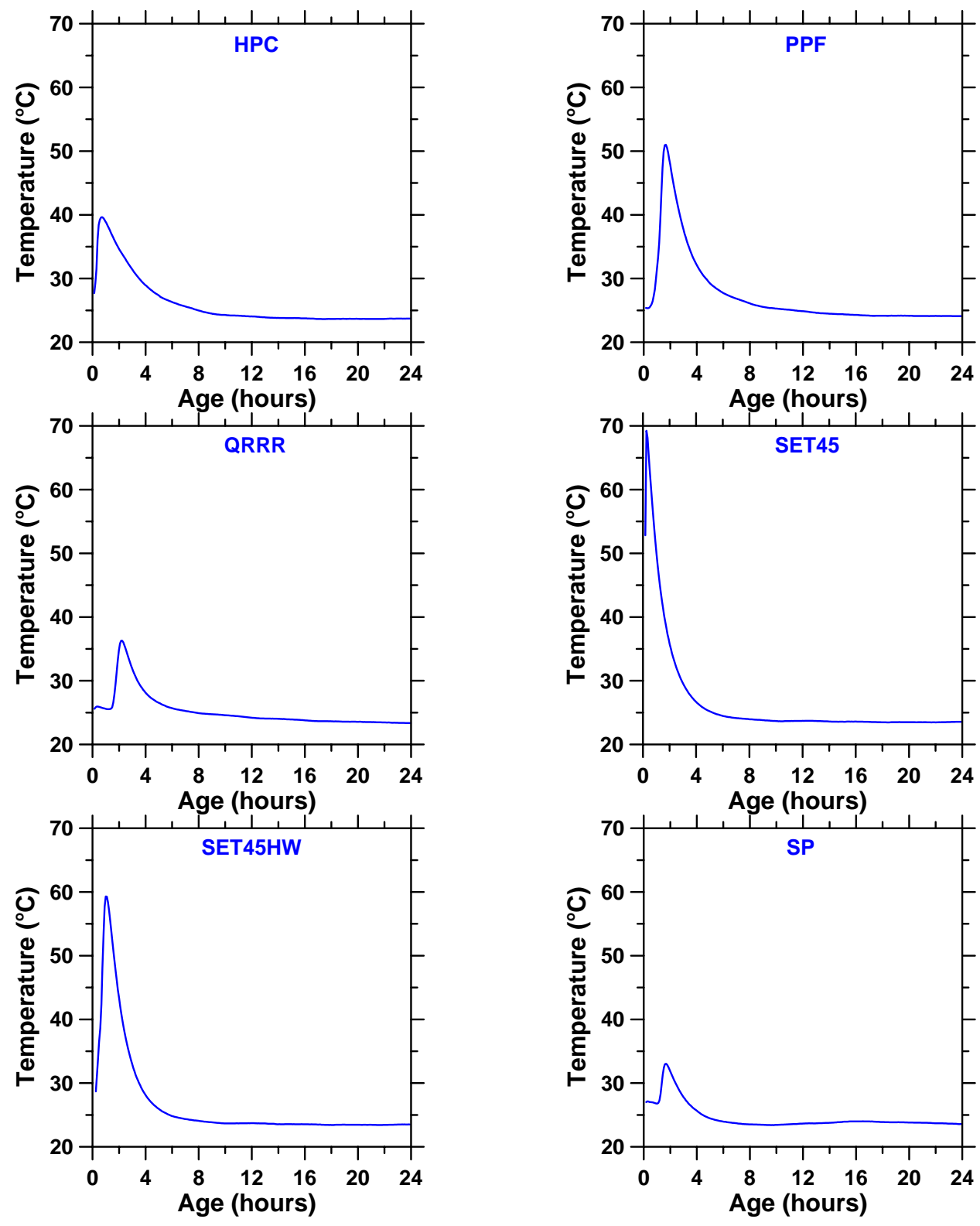


Figure 5.13 Temperature Rise in Rapid Repair Mortar Samples

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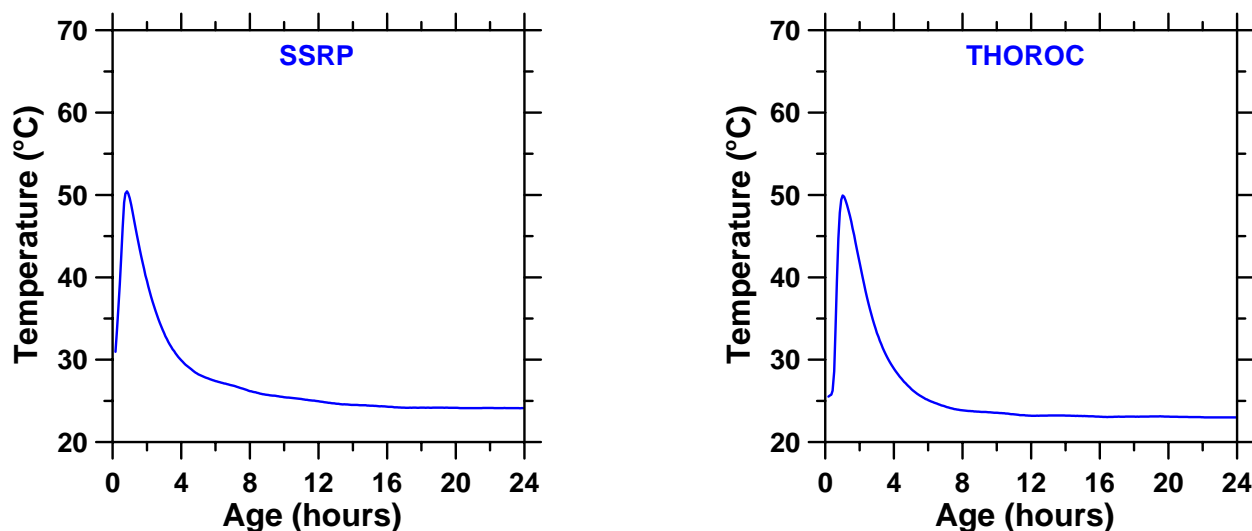


Figure 5.13 Temperature Rise in Rapid Repair Mortar Samples
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5.2 Volumetric Stability And Early-Age Cracking Potential

The experimental program for characterizing the volume change behavior of the various repair materials consists of measurements of unrestrained length change and restrained shrinkage using the ring test. The unrestrained length change consists of the average of two measurements. The measurements were begun from the time of set (as determined with the Vicat test) using a non-contact laser while the specimen was in the mold followed by standard length change tests that are performed in accordance with ASTM C-157. All of the specimens were sealed during the first 6 hours and either sealed or exposed to drying from two opposite faces of the cube (i.e., the ends and two non-adjacent sides of the cube were sealed) at an age of 6 hours. The sealed shrinkage corresponds to the length change measured in the sealed specimen while the total length change corresponds to the shrinkage measured in the specimen exposed to drying from the

two faces. The drying shrinkage is taken as the difference between these two measurements. The temperature effects were subtracted from the overall length change by assuming a coefficient of thermal expansion of 10×10^{-6} mm/mm °C. The restrained ring tests were performed using the ring specimens described in Chapter 3. Strain measurements began at the time of placement using 4 strain gages placed on the inner surface of the ring. The strains were converted to a residual stress using the ARC2 software which was developed at Purdue based on equations from (Hossain et al. 2002). The tensile strength was estimated as 75% of the flexural strength as measured earlier in this chapter. By plotting the ratio of the residual stress to tensile strength the cracking potential of the specimens can be assessed. While theoretically the specimens can be expected to crack when this ratio equals a value of 1, prior experimental programs have demonstrated that cracking can occur any time after this stress level exceeds 0.7. The following section describes each of these properties in greater detail.

5.2.1 Volume Stability (Autogenous and Drying Shrinkage)

Figure 5.14 provides a description of the average volume change that was measured on a 3" x 3" x 15" specimen from the time of set. The data describes the measurements from a specimen that was exposed to drying at an age of 6 hours (total) and a specimen that was sealed from drying (note this data was assembled by combining laser measurements with measurements from the comparator). Substantial differences can be observed in the length change of the materials tested. The greatest shrinkage was observed to occur in the BASE mixture ($-780 \mu\epsilon$) while several mixtures showed very low magnitudes of shrinkage (less than $-200 \mu\epsilon$ QRRR, SET45, SET45HW, SP). It can also be observed that several of the materials (DOTP, EMACO, QRRR, SET45, SET45HW, SP, and SSRP) demonstrate very little length change after the first few days.

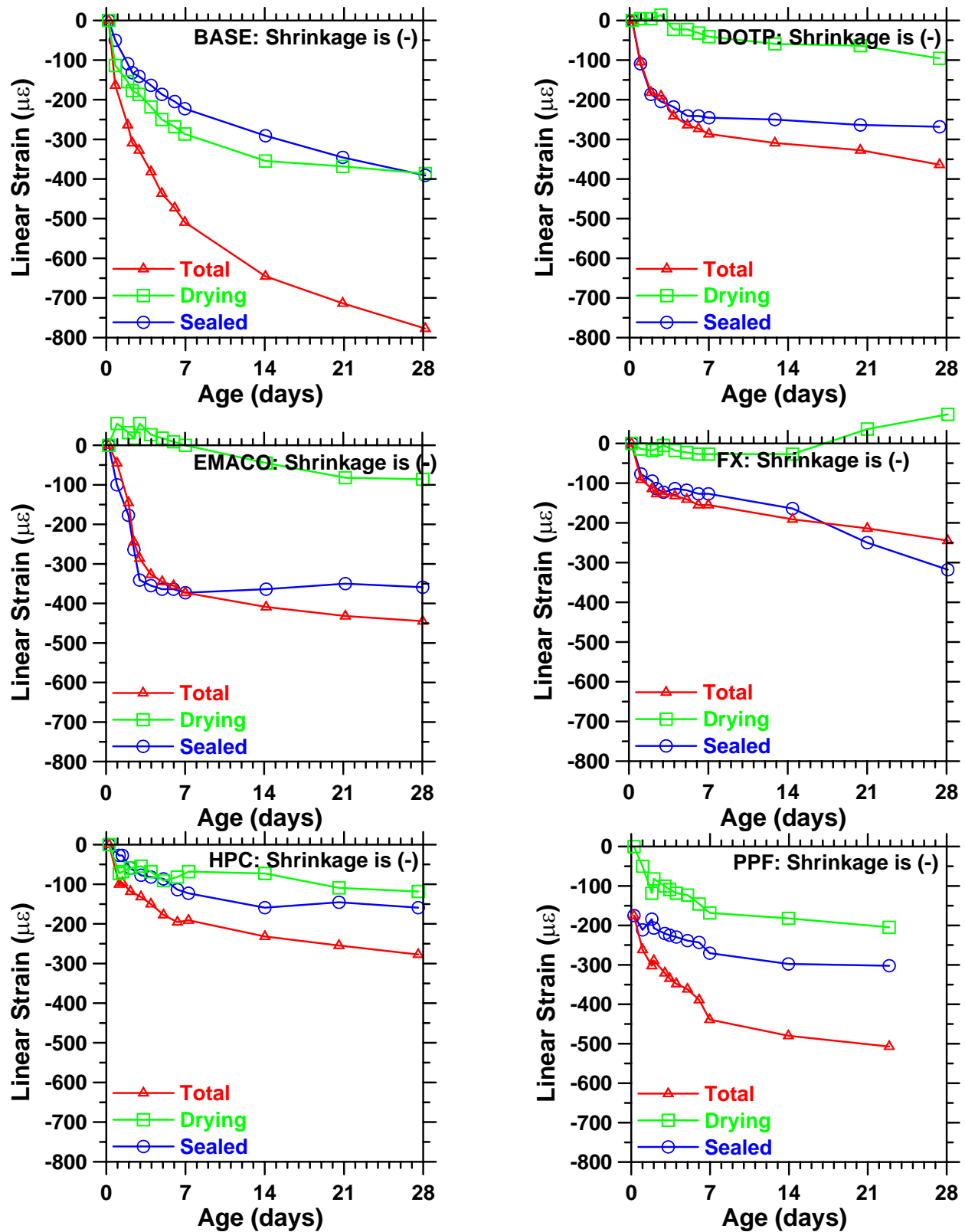


Figure 5.14 Volume Change Measurements in Repair Materials Over 28 Days

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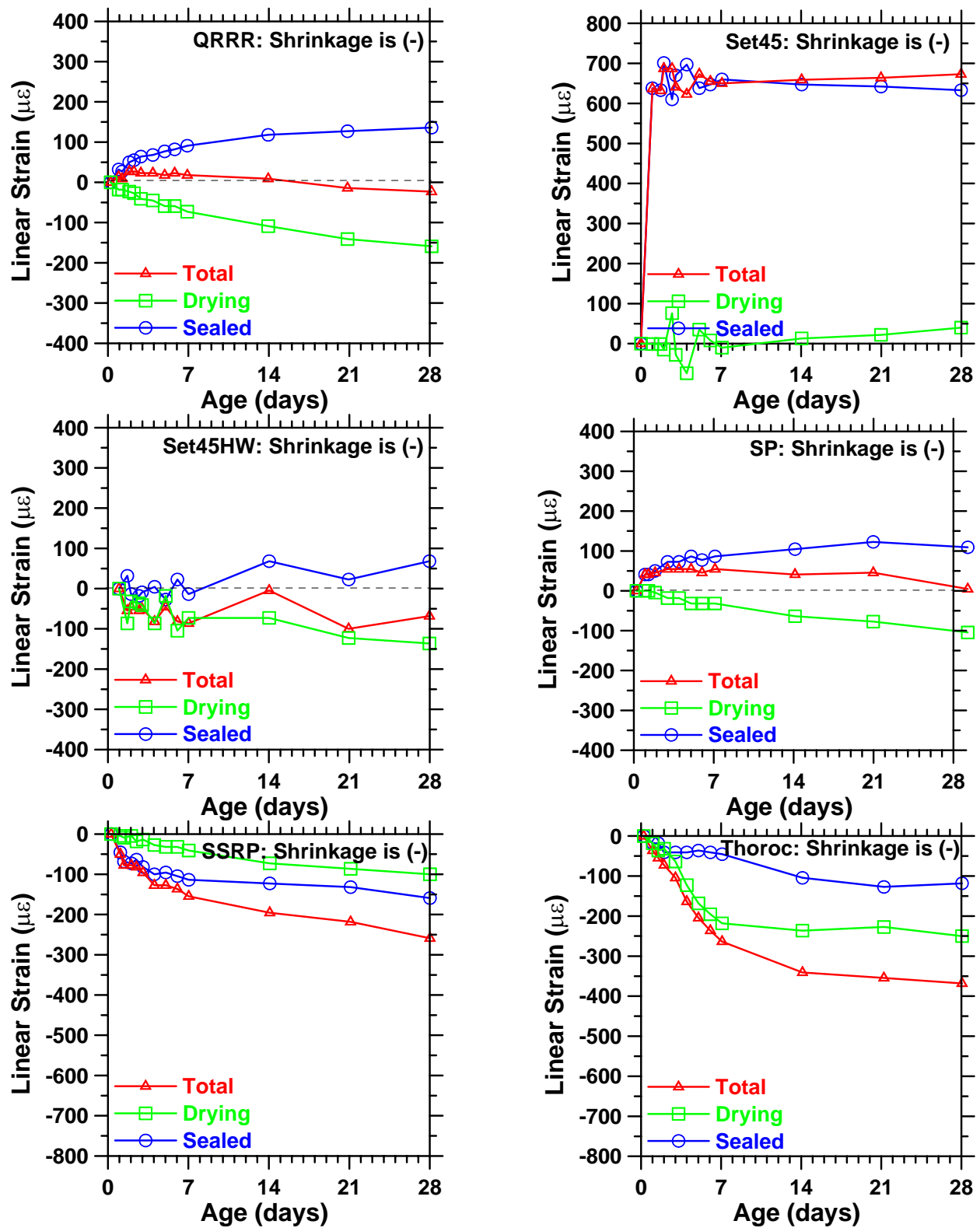


Figure 5.14 Volume Change Measurements in Repair Materials Over 28 Days

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5.2.2 Restrained Shrinkage

Figure 5.15 shows the ratio of the residual stress in the repair material and the tensile strength over the first 7 days of the materials life. A wide range of material behaviors can be observed, though the stresses generally begin to develop slightly after the time of set. It should be noted that these measurements have not been corrected for any changes in temperature which may influence the measurements during the first 8 hours. It can be seen that the majority of the mixtures show a relatively low cracking potential which implies that these materials should perform well in field applications. Several materials show virtually no change in the residual stress after the first day (QRRR, SET45, SET45HW, SP and SSRP). Other materials (EMACO, HPC, PPF and THOROC) demonstrate behavior that is more of a cause for concern as the cracking potential in these materials is high (between 0.4 and 0.8 at 7 days) and the potential appears to be rising over time.

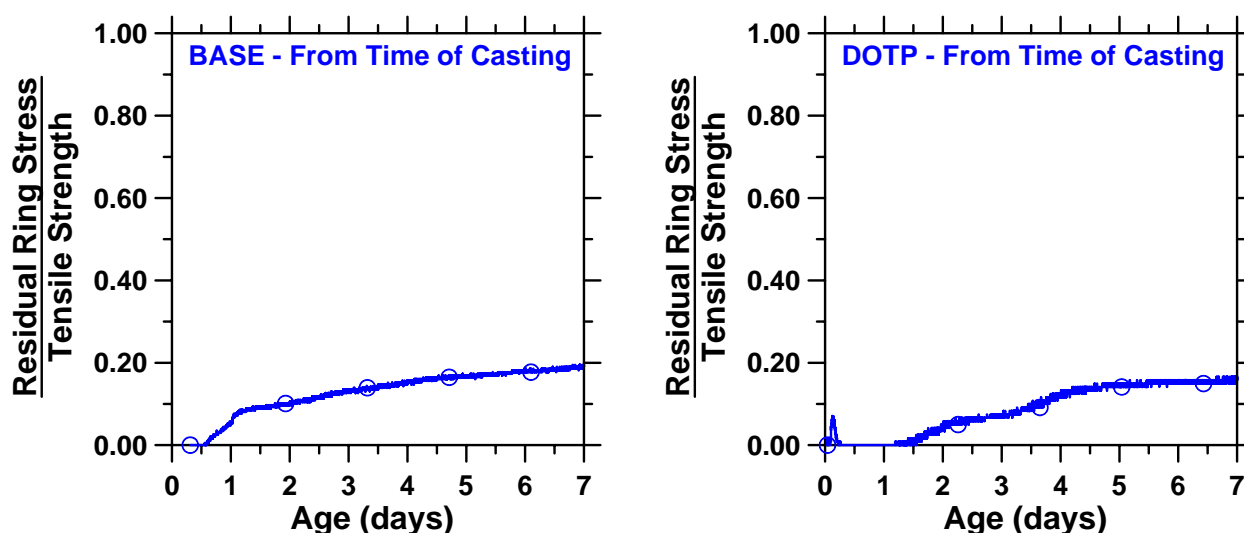


Figure 5.15 Cracking Potential as Assessed Using the Restrained Ring Test for Repair Materials for 7 Days after Casting (Continued on the Next Page)

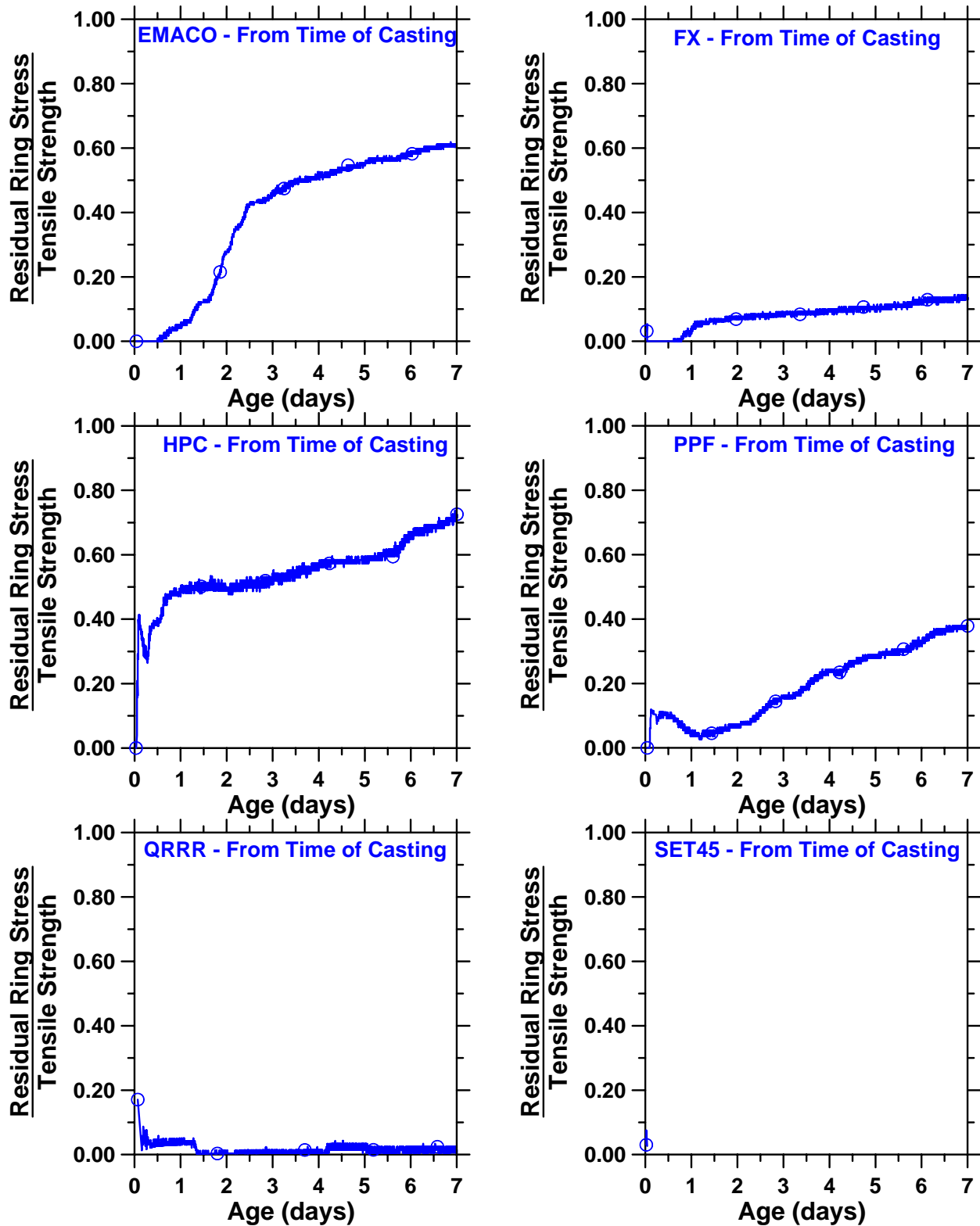


Figure 5.15 Cracking Potential as Assessed Using the Restrained Ring Test for Repair Materials for 7 Days after Casting (Continued on the Next Page)

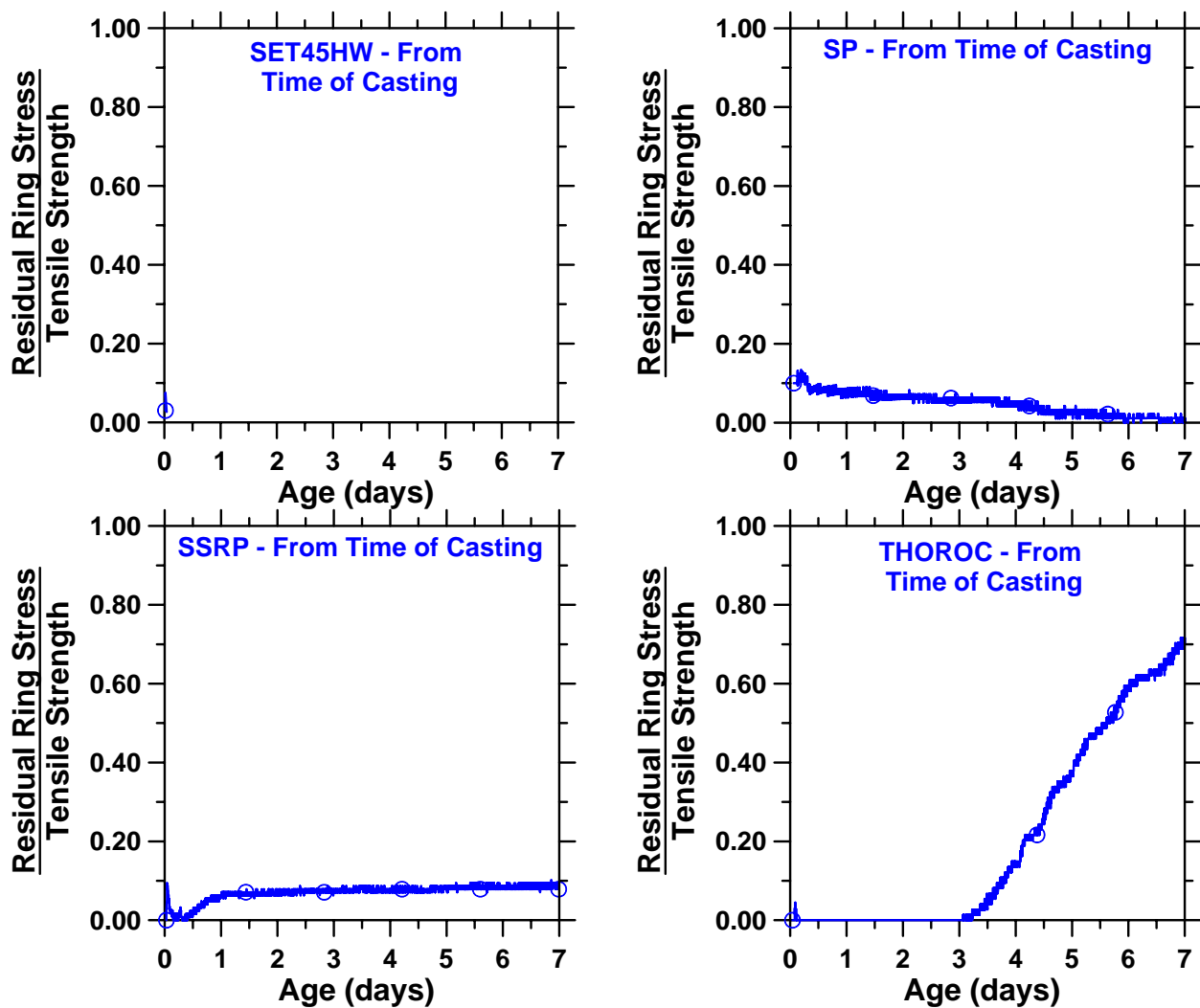


Figure 5.15 Cracking Potential as Assessed Using the Restrained Ring Test for Repair Materials for 7 Days after Casting (Continued from the Previous Page)

Figure 5.16 was developed to try to summarize the results from the ring test by plotting the ratio of the residual stress that was measured in the ring and the tensile strength (at an age of 7 days). This ratio is frequently referred to as the cracking potential since as this ratio approaches 1 the potential for cracking increases. It can be seen that several materials (QRRR, SET45, SET45HW, SP, and SSRP) demonstrate a very low cracking potential (< 0.1) while the BASE, DOTP, and FX materials have a cracking potential of less than 0.2 at 7 days.

These low values occur for two reasons, first these materials typically show relatively low values for unrestrained shrinkage (Figure 5.14). Second many of these materials have an expansion at early ages. While in practice this may imply that the repair material may be slightly ‘compressive prestress’ as it expands in the repair, this prestressing effect is typically not seen in the restrained ring. This limitation occurs since the concrete would come out of contact with the restrained ring during expansion and the ring would be ‘stress free’. If the concrete shrinks from this expanded state it will not generate a stress in the material until it reaches its original size and begins to compress the ring with further shrinkage. This highlights a limitation of the ring test that needs to be considered in assessing the results from the test. Due to this limitation a dual ring system has been suggested (Pease and Weiss 2004) with an instrumented outer ring that limits expansion and enables the expansive stresses to be quantified and an inner ring that functions like the standard ring test.

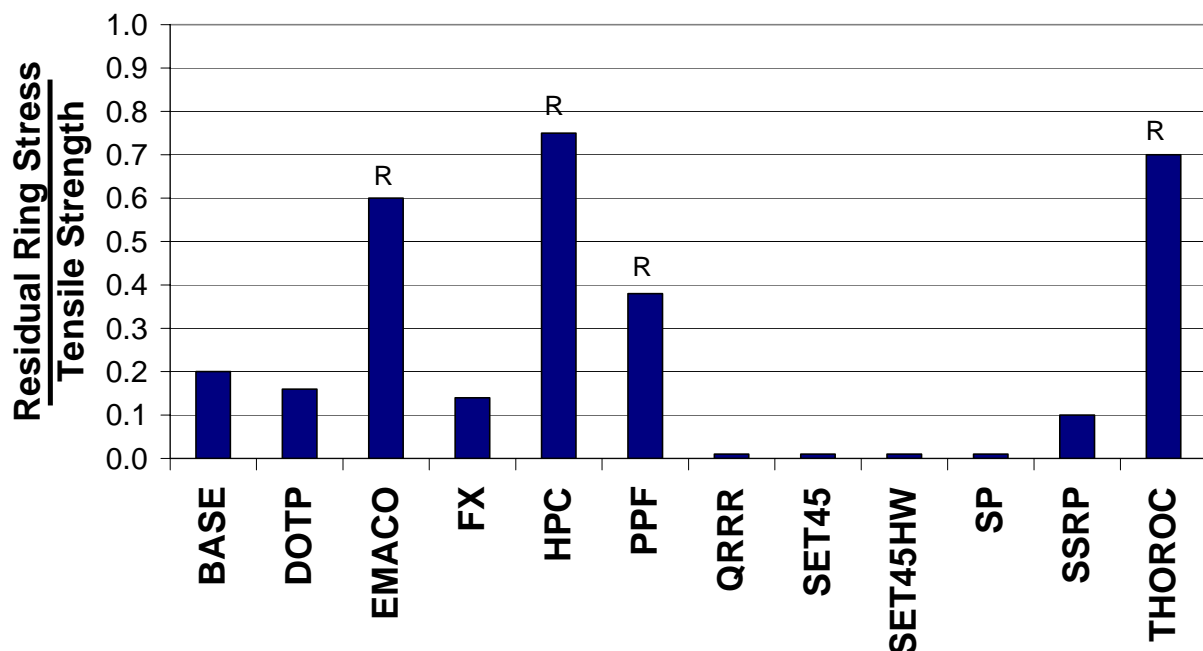


Figure 5.16 Cracking Potential (Residual Strength/Tensile Strength in Restrained Repair Materials at an Age of 7 Days (R denotes rising cracking potential)

It can be seen that four of the mixtures have a cracking potential between 0.4 and 0.8 (EMACO, HPC, PPF, THOROC). These materials have a built in residual stress and additional stresses from loading or temperature changes may result in the development of cracking. It is also interesting to note that the materials with these higher cracking potentials also appear to have these values rising at 7 days presumably due to the continued drying shrinkage.

5.3 Mechanical Bond

Achieving adequate bond between repair materials and the existing concrete substructure is a key need of any repair material. This bond information is needed to insure adequate stress transfer during loading, expansion, and contraction. Various techniques are used to prepare the subsurface that may result in different degrees of mechanical and chemical bond between the subsurface and the repair patch. Currently INDOT utilizes the slant shear test as an acceptance method to evaluate the bond quality. This test provides a reproducible value for comparison purposes, however the applicability of the results depends on the actual subsurface preparation method used in the field. This work will focus on distinguishing between shear and tensile strength of the bond. As such two tests were performed as described in Chapter 3. Specimen surfaces will be prepared with different roughnesses (a smooth saw-cur surface and a rough fractured surface) to better quantify the contribution of the bond as either a chemical or physical process for the different materials. By distinguishing between the two aspects of this bond (shear and tensile) it is hoped that insight will be able to be gained for use in assessing not only the initial bond strength. The following section describes the average results obtained from two specimens which were tested for each condition 1) smooth-shear, 2) rough-shear, 3) smooth-tension, 4) rough-tension at an age of seven days.

Figure 5.17 illustrates the shear bond strength measured on both a rough and smooth surface. It can be seen that, as one may expect, the bond strength is higher in nearly every case on a rough surface since the rougher surface will have a greater surface area and a greater probability of developing a mechanical interlock than the smooth surface.

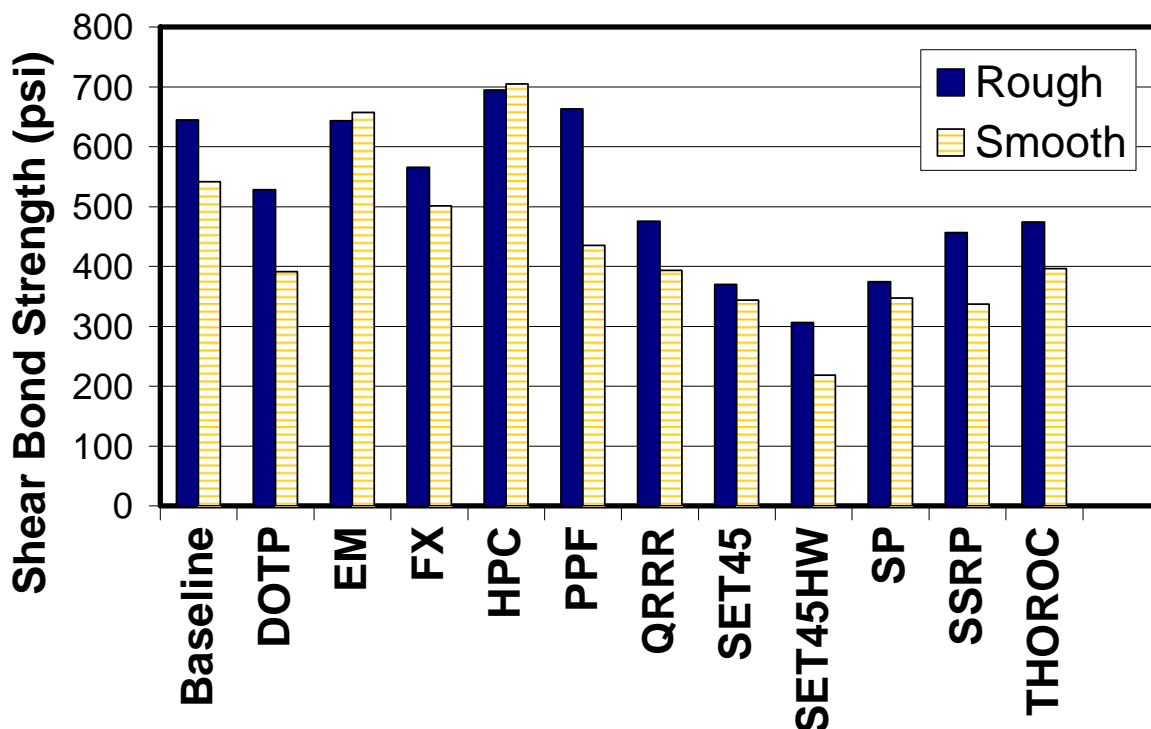


Figure 5.17 Shear Bond Strength for Repair Materials on a Rough and Smooth Surface at 7 Days

Figure 5.18 illustrates the bond strength measured in tension on both a rough and smooth surface. It can be seen that the tensile strength (also referred to as the pull-off strength) is less than the strength in shear. Again the rough surfaces generally have a higher strength than the smooth specimens. It should also be noted however that more scatter exists in the tensile strength results since these specimens are more sensitive to voids in the bond.

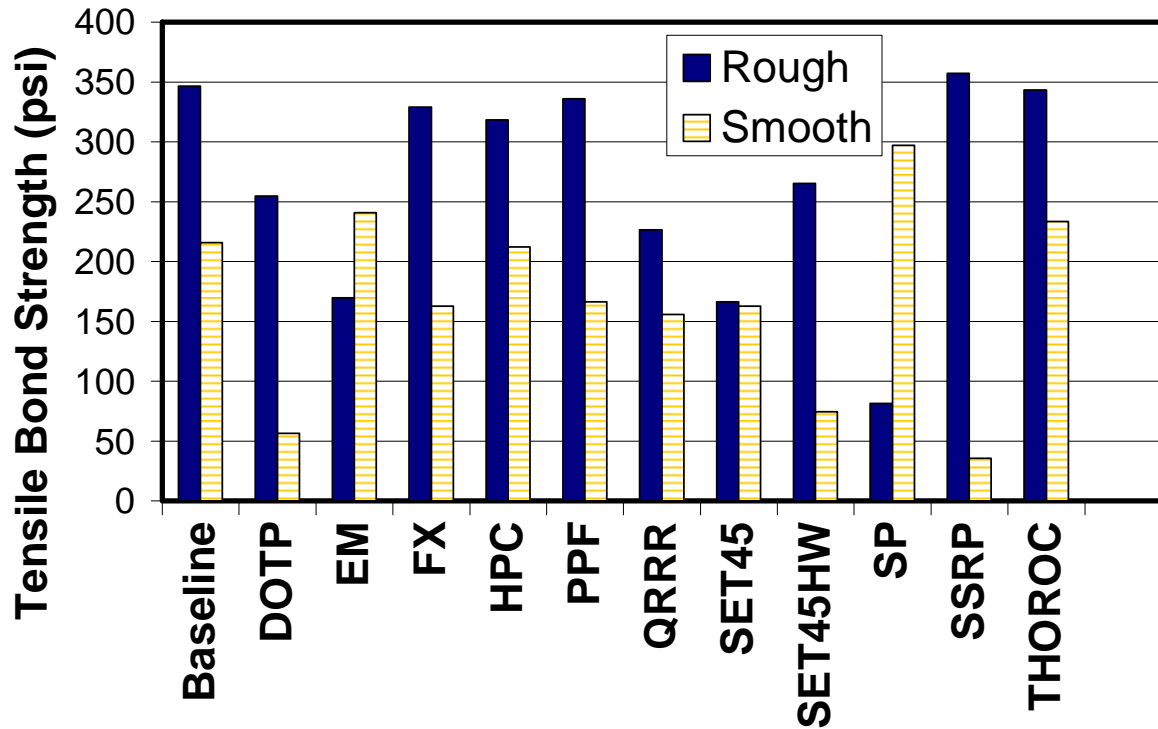


Figure 5.18 Tensile (Pull Off) Bond Strength for Repair Materials on a Rough and Smooth Surface at 7 Days

5.4 Ultrasonic Wave Velocity

Figure 5.19 illustrates the ultrasonic wave velocity measured in cylindrical specimens at early ages. The ultrasonic wave velocity measurements were originally thought to provide a rapid method for assessing the elastic modulus development (elastic modulus is theoretically related to the square of the wave speed). In comparing the square of the wave velocity with the measurements of the elastic modulus in compression, clear trends were not originally evident. It should be noted that the rate coefficient was determined for the square of the velocity and the results are presented in Table 5.1.

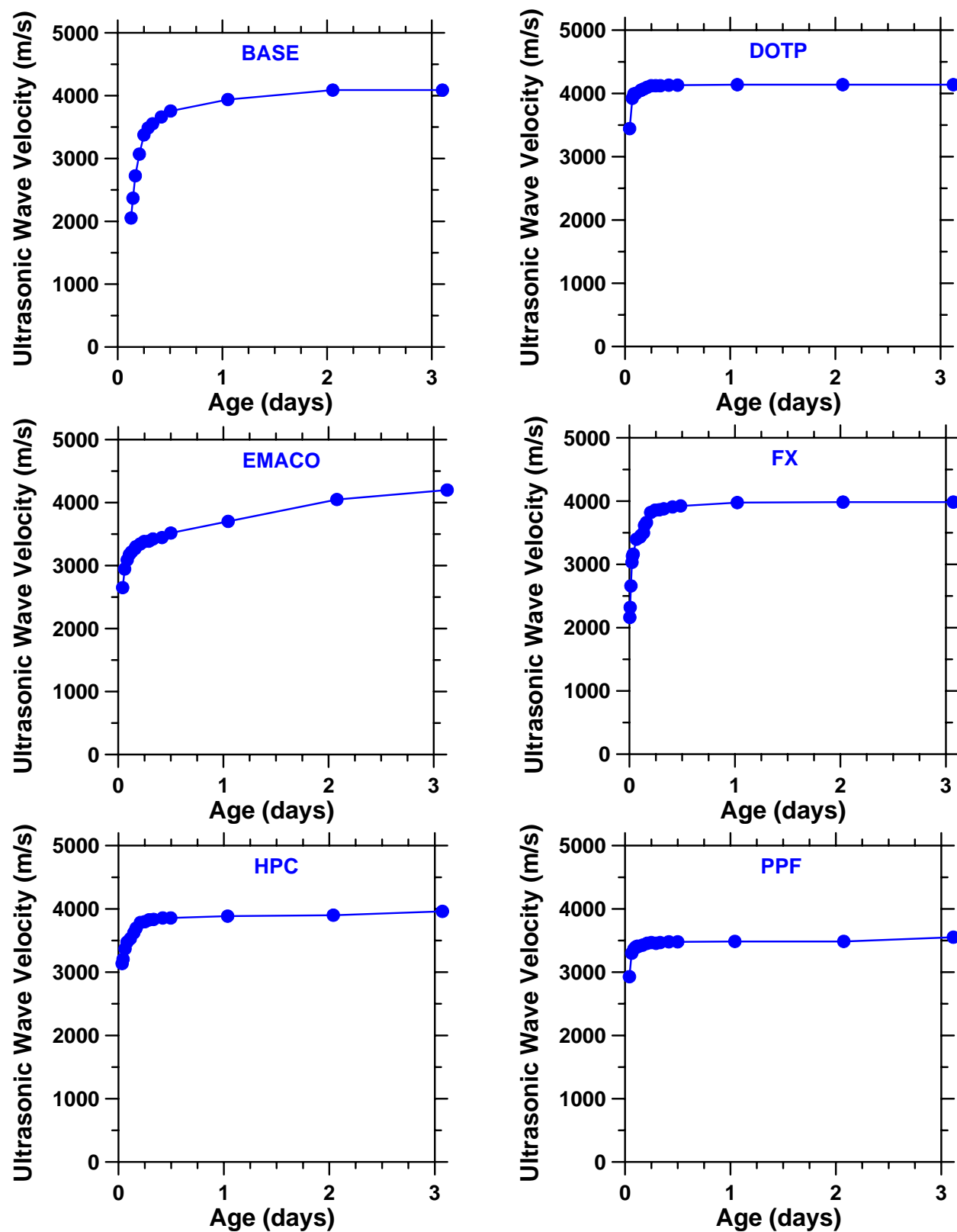


Figure 5.19 Ultrasonic Wave Velocity in Rapid Repair Materials
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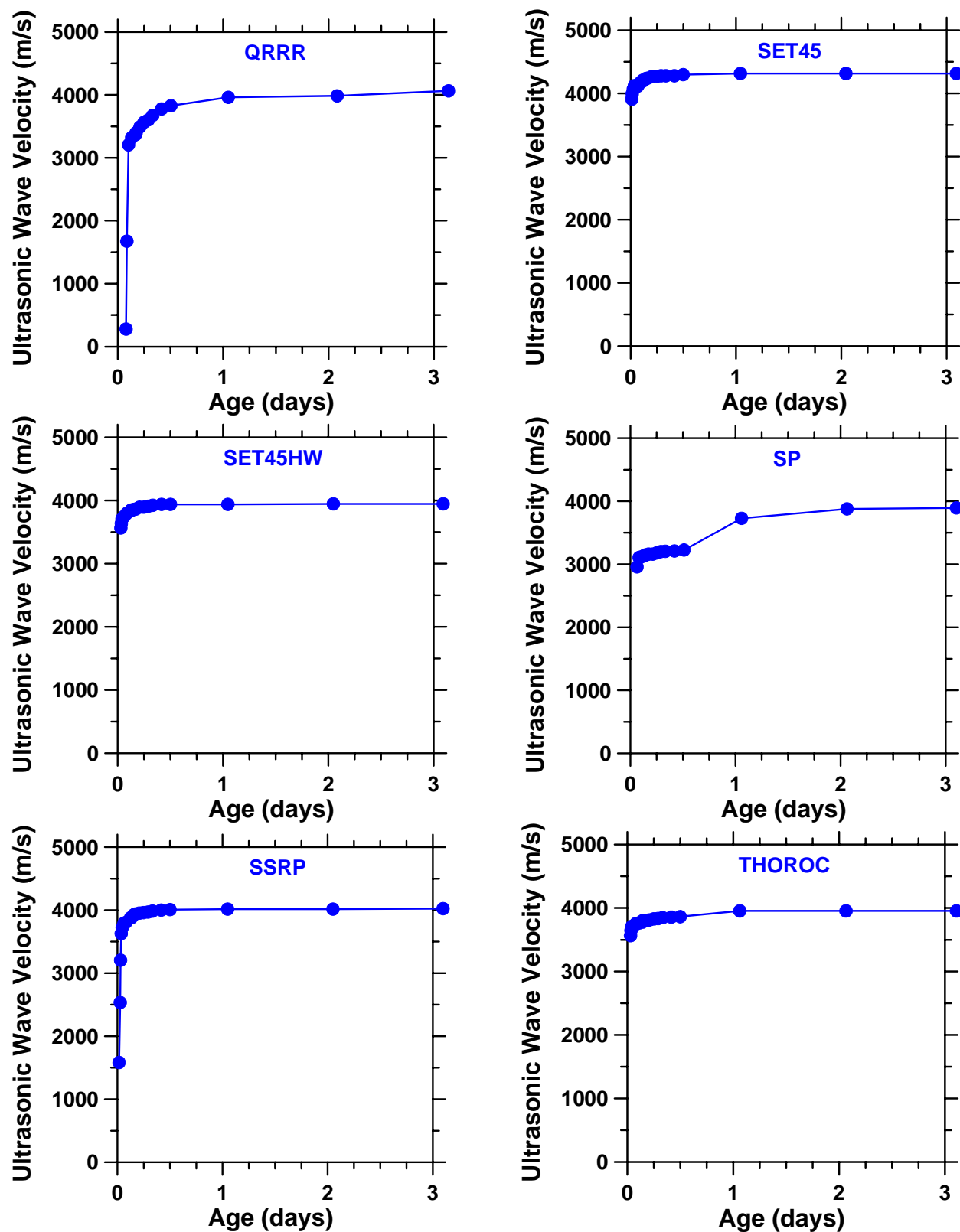


Figure 5.19 Ultrasonic Wave Velocity in Rapid Repair Materials
(Continued from the Previous Page)

5.5 Summary and Conclusion

In summary, this chapter has provided a detailed description of the results obtained from the laboratory testing portion of this research. Table 5.1 provides a summary of results obtained from the materials tested. Table 5.1 contains information on the initial set, final set, long term values for compressive strength, flexural strength, elastic modulus, and ultrasonic wave speed. In addition Table 5.1 provides rate constants to describe the development of compressive strength, flexural strength, elastic modulus, and ultrasonic wave speed (squared). In addition, results are presented from the unrestrained shrinkage tests, restrained ring tests, and bond strength tests.

Due to the wide range of applications that these materials may be used in, it does not appear prudent to rank the materials, rather this table should be used by the INDOT to determine which of the following materials may be suitable for a specific application. It should also be noted that this table only provides information about the mechanical properties, volume stability, and bond strength. Further testing is necessary to evaluate the durability of these materials.

Table 5.1 Summary of Material Properties Tested (Continued on the Next Page)

Material	Setting Time			Compressive Strength		Flexural Strength		Elastic Modulus		Ultrasonic Wave Speed	
	Initial Setting Time	Final Setting Time	M_o (°C*day)	S_{∞}	$C-K_t$	S_{∞}	$F-K_t$	S_{∞}	$m-K_t$	S_{∞}	$U-K_t$ (for S^2)
	minutes	minutes	°C*day	psi	psi/°C/day	psi	psi/°C/day	psi	psi/°C/day	m/s	m ² /s ² /°C/day
BASE	105	139	2.220	10060	2.5	1332	2.6	4793043	6.6	4179	12.7
DOTP	42	48	0.763	6863	10.6	812	5.2	4908046	25.6	4159	139.2
EMACO	23	33	0.521	4130	1.4	734	0.9	5607692	2.2	4414	6.6
FX	9	10	0.163	7477	5.2	768	12.6	5367522	12.9	4048	40.2
HPC	24	27	0.431	6433	13.4	530	9.1	4520364	14.3	3981	30.3
PPF	42	50	0.799	6011	1.2	645	10.9	4131793	2.1	3557	109.1
QRRR	80	89	1.422	7336	1.6	619	2.7	4272472	4.1	4081	21.7
SET45	8	9	0.147	5277	87.5	492	4.3	5244494	5.5	4319	153.5
SET45HW	38	41	0.655	5538	12.8	460	33.1	5100000	16.1	3961	116.6
SP	75	81	1.294	4237	0.1	548	0.1	3068949	0.5	3928	3.8
SSRP	13	20	0.315	7051	11.3	740	27.2	5193319	20.2	4033	138.5
THOROC	32	35	0.561	5070	17.7	430	12.7	4438566	11.0	3971	103.9

Table 5.1 Summary of Material Properties Tested (Continued from the Previous Page)

	Activation Energy	Temperature	Volume Stability			Bond			
<i>Material</i>	E_A	Maximum Temperature	28 Day Autogenous Shrinkage	28 Day Total Shrinkage	Cracking Potential at 7 Days	Shear Bond Strength (Smooth)	Shear Bond Strength (Rough)	Tensile Bond Strength (Smooth)	Tensile Bond Strength (Rough)
	J/mol	°C	μϵ	μϵ	~	psi	psi	psi	psi
BASE	55816	31.5	-390	-780	0.20	542	645	216	347
DOTP	64781	50.3	-270	-360	0.16	392	528	57	255
EMACO	6545	37.4	-360	-450	0.60	657	643	241	170
FX	22312	39.8	-318	-245	0.14	501	566	163	329
HPC	27685	39.7	-159	-277	0.75	705	695	212	318
PPF	28270	51.0	-302	-507	0.38	435	663	166	336
QRRR	18163	36.3	127	-10	~	394	476	156	226
SET45	31099	69.3	630	690	~	343	370	163	166
SET45HW	63495	59.3	70	-70	~	218	307	74	265
SP	10271	33.0	110	10	~	347	374	297	81
SSRP	43079	50.4	-130	-220	~	337	456	35	357
THOROC	5129	49.9	-120	-370	0.70	396	474	233	343

In conclusion, it is recommended that Table 5.1 be used for the selection of laboratory mixtures to investigate for use in the follow-up study on evaluating the field performance of joint repairs. It is anticipated that for that application the desirable material characteristics would include rapid setting and strength development, volumetric stability and good bond properties (especially for sawed surfaces). Materials like BASE should be discouraged when they are in contact with reinforcement due the chlorides that are used in these materials which could lead to corrosion. In addition, BASE has a relatively large aggregate size which may make their use difficult. EMACO, PPF, QRRR, and SP show a relatively slower strength gain than the other materials shown in this table and as such those materials may not enable the most rapid opening of the pavement to traffic. As such it appears that FX, SET45, SSRP should be considered for the next phase of the study with possible consideration of HPC and THOROC if the potential for residual stress development due to restrained shrinkage can be reduced.

CHAPTER 6: GUIDELINES FOR GOOD REPAIR PRACTICES

6.1 Introduction

This chapter reviews good practices and precautions that are to be followed while preparing for and performing bridge deck patch repairs. As suggested by the SAC, this chapter has been compiled using information in literature and observations from the field visit where the entire patch repair process was documented in detail. This chapter is intended to serve as a guideline for use by highway agencies in the field.

This chapter specifically focuses on reviewing the repair of a spalled concrete section. Spalling is a common distress in concrete pavements and bridge decks that reduces service life and can be hazardous to highway users (FHWA, 1999). A spall in a concrete surface may be the result of localized distress or could be indicative of more widespread distress in the concrete. Common causes of spalls include corrosion of reinforcing steel, an inoperative joint resulting from incompressibles in the joint, misalignment of joint dowels, freezing and thawing of non-air-entrained concrete in a critically water-saturated condition, freezing and thawing of porous aggregate in a critically water-saturated condition, or alkali-silica reaction (REMR Technical Document, 1994).

6.2 Location of Repair Documented in This Report

The field observations in this report are based on a field visit to I-65 on August 5, 2003. Patch repair was performed in the northbound lane of the Big Blue River Bridge (Location I0657308) between 8.30 AM and 3.00 PM. Figures 6.1 (a and b) illustrate the extent of deterioration on the bridge. This repair was necessitated due to the failure of patches in spite of the fact that some of them were repaired just last year. Some patches demonstrated corner-brakes indicating a possibility of failure due to loading. The failure could have also occurred due to the unfilled saw-notches from the previous repairs (Figure 6.1c).



Figure 6.1a: Image of the Section to be Repaired

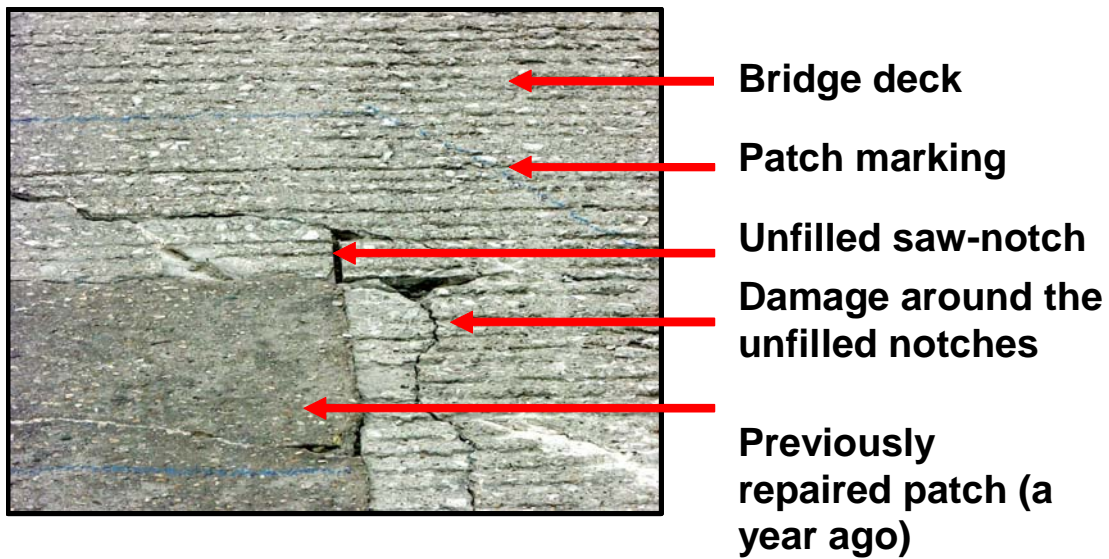


Figure 1b: Close-up View of the Section to be Repaired



Figure 1c: Pavement damage at unfilled saw-notches from previous repairs

6.3 Traffic Control and Safety Measures

Any partial-depth patching operation requires adequate traffic control which ensures a safe working environment for the maintenance crew and safe travel for vehicles in the construction area. Traffic control operations should be planned so that they cause the least possible amount of disturbance in the flow of traffic. In this repair the Amity 002 unit provided the required traffic control and support help. Some of the critical safety precautions that must be followed include the use of barricades that clearly demarcate the repair area from the usable pavement, and the use of reflective gear, protective helmets and safety shoes for all the workers.

Though the work was scheduled to commence at 8.00 AM, the start of repair was delayed by about half-hour due to the prevailing foggy atmosphere. The barricades demarcating the repair zone were put in place only after the fog had cleared off to ensure the safety of commuters and workers. All the equipment for the repair process was stationed near the site so that work could begin as early as possible. Figure 6.2 shows all the equipment parked at the site. Most rapid-setting materials used for partial-depth repair require special safety precautions for protecting the maintenance workers using them, and for protecting the environment. It is therefore important that highway agencies follow all instructions regarding worker protection and repair material disposal, which are available from the manufacturer in the form of Material Safety Data Sheets (MSDS). In this study, the workers used protective gloves and goggles in keeping with the material

specifications for Set-45, the magnesium phosphate based proprietary rapid-setting material that was used for repairing the patches.



Figure 6.2: Barricades delineating the repair zone, and the equipment within the zone. It is crucial that workers follow safety precautions during the repair process for both traffic safety and safety in handling the repair material

6.4 Steps Involved In Partial-Depth Repair

The process of solving concrete repair problems includes repair analysis, strategy and design (Emmons, 1993). A comprehensive evaluation identifying the cause and effect of deterioration should be the first step of any repair process. This should be

followed by a thorough analysis of the effect of the repair on the structure, and the durability, constructability and compatibility of repair with the existing structure. The spall repair process typically consists of the following steps, as observed from the INDOT field visits and survey of literature:

- (1) Preliminary inspection to determine the extent and details of damage, evaluate the cause of distress, and delineate the repair boundaries,
- (2) Removal of the deteriorated concrete and surface preparation,
- (3) Mixing and placing of the repair material,
- (4) Finishing the repair material,
- (5) Cleaning up of the parent surface and tools, and
- (6) Re-opening the pavement to traffic, after the stipulated curing time.

Each of these steps is dealt with in greater detail in subsequent sections.

6.4.1: Step 1: Identification of Boundaries for the Repair

The first step in patch repair involves performing a preconstruction survey to identify the areas of deterioration and mark the actual repair boundaries. This is usually done by striking the surface of the concrete using a hammer, steel rod, or by dragging a chain along the surface, and listening to the sound produced (Emmons, 1993; ACI Repair Manual, 1999). A sharp, metallic ring indicates sound concrete while a dull, hollow sound indicates areas of delaminated concrete. During the INDOT field visit, the supervisor used a hammer to gauge the extent of deterioration in order to mark the boundaries of repair. Sounding was started along the pavement transverse joint and mid-slab areas that exhibited visible spalling and severe scaling, as suggested in the literature.

It is also important avoid irregular shapes and re-entrant corners while marking the repair boundaries as this would greatly increase the potential for cracking. Excessive or complex edge conditions result in shrinkage stress concentrations and cracking (Emmons, 1993; ACI Repair Manual, 1999). As a result it is best to use simple rectangular and trapezoidal boundaries.

For selecting the dimensions for the repair area, the following guidelines are specified in literature (Emmons, 1993; Wilson et al. 1999). The repair patch should be at least 100mm wide, 250mm long, and 50mm deep for weight and volume stability. If the patch is less than 150mm long and 40mm wide, it is usually filled with a sealant. Patches less than 300mm apart need to be combined into a single patch. The INDOT supervisor on the field adhered to these guidelines while deciding the patch dimensions. The average dimensions of a patch in this study were 800mm X 450mm X 150mm. A total of six patches were identified for performing partial-depth repair. Once the patch boundaries were marked with paint, saw cuts were made around the perimeter of the repair area as illustrated in Figure 6.3. It is important not to cut any reinforcing steel while providing a saw-cut that is sufficient enough to facilitate removal of the deteriorated concrete by sawing and chipping. In the INDOT site visit the saw-cuts were approximately 50mm deep, provided vertical faces at the repair edges and sufficient depth to prevent spalling of the repair material along the repair perimeter.

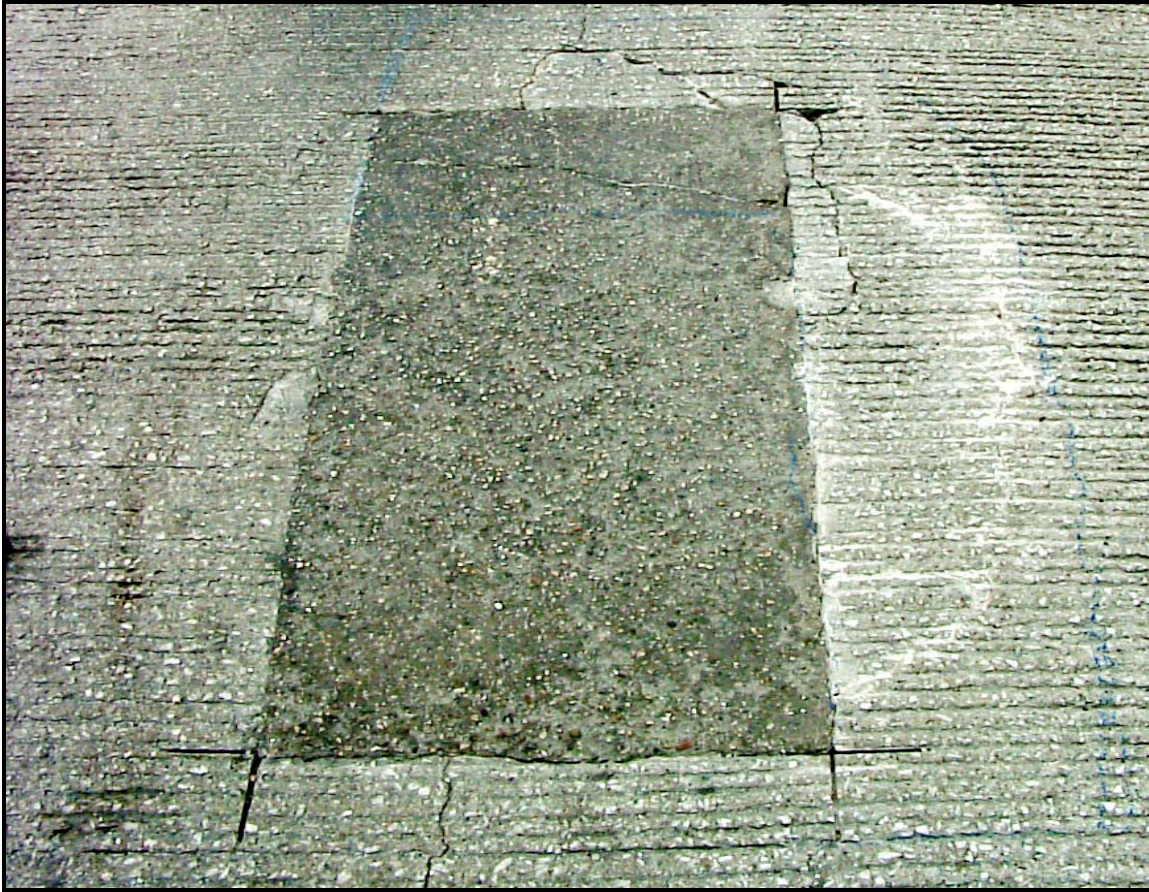


Figure 3: Saw cuts delineating the delaminated patch

6.4.2 Step 2: Removal of deteriorated concrete

The next step, after saw-cutting was to chip away the deteriorated concrete until sound and clean concrete was exposed. This process was undertaken one patch at a time. Some of the commonly employed removal tools for this process include pneumatic chipping hammers or pneumatic scabblers, rotary milling machines or hydro removal (Emmons, 1993). In the case-study of the INDOT site visit, a 15-lb hand held jackhammer was used for chipping. The hammer was held at a 45 degree angle so that there was minimal damage to the sound concrete. Though additional saw cuts are sometimes made within the repair area in order to expedite concrete removal by chipping,

it was not done in this case. Studies have shown that jackhammers heavier than 30-lb may damage and fracture the sound concrete, and in some cases break through the slab completely. Even while using the lighter 15-lb jackhammer, sufficient care was taken not to damage the reinforcing steel that was encountered during chipping. As specified in literature (REMR Technical note, 1994), the removal of concrete began at the interior of the repair area and progressed toward the boundaries. Figure 6.4 illustrates the use of the jackhammer for removing the deteriorated concrete. Figure 6.5 illustrates the repair patch, after some of the chipping was performed.



Figure 6.4: Jackhammer being used for chipping away the deteriorated concrete



Figure 6.5: The surface of the patch after some chipping was performed

6.4.3 Step 3: Surface Preparation

Surface preparation involves the process of conditioning the existing concrete to receive repair materials and is one of the critical phases of site work (Emmons, 1993). Once the unsound concrete has been removed, the exposed faces should be thoroughly cleaned to remove oil, dust, loose particles and joint-sealant particles. This is important as the absorption of the repair material into the substrate's pore structure is an important mechanism by which bond is established (Emmons, 1993). If the pore structure is

clogged with dust or other contaminants, it hinders the absorption process and reduces bond strengths.

Sandblasting is a common technique that is used for removing the loose particles, oil, dust, traces of asphaltic concrete and other contaminants before placing patching materials. Sandblasting, however, generates a lot of dust and is sometimes replaced with high-pressure water-blasting, particularly in urban environments where controlling dust is critical. In the INDOT field visit, sand-blasting was used, as illustrated by Figure 6.6. This was followed by air-blowing for removing dust and sand-blast residue. Figure 6.7 shows the repair patch after it had been air-blown. As stipulated in literature, (FHWA, 2003), debris was blown out and away from the patch so that wind or passing traffic cannot carry it back into the patch.



Figure 6.6: Removing dust and sand-blast residue with compressed air



Figure 6.7 A Close-up View of the Cleaned Patch

One of the other points that merits consideration is that prior to preparation of concrete surfaces, the exposed reinforcing should be inspected for proper exposure, clearance, cross-sectional area, and location. Heavy rust layers that build up on reinforcing steel during the corrosion process cause concrete delamination and spalling (Emmons, 1993). One of the primary causes of patch failure is due to insufficient cleaning of the corroded bars. Proper cleaning of the corroded bars requires removal of concrete around the full circumference of the bar, by which the contaminated concrete can be removed. Some of the other reasons for removing the concrete around the bar are

for facilitating the encapsulation of the repair material around the bar, for providing a relatively uniform electro-chemical environment, and for anchoring the repair to the substrate (Emmons, 1993). Figure 6.8 shows the INDOT supervisor inspecting the repair patch to ensure that the concrete surrounding the rebar has been adequately removed, while Figure 6.9 shows the repair patch after all the concrete in the vicinity of the reinforcing steel has been removed.

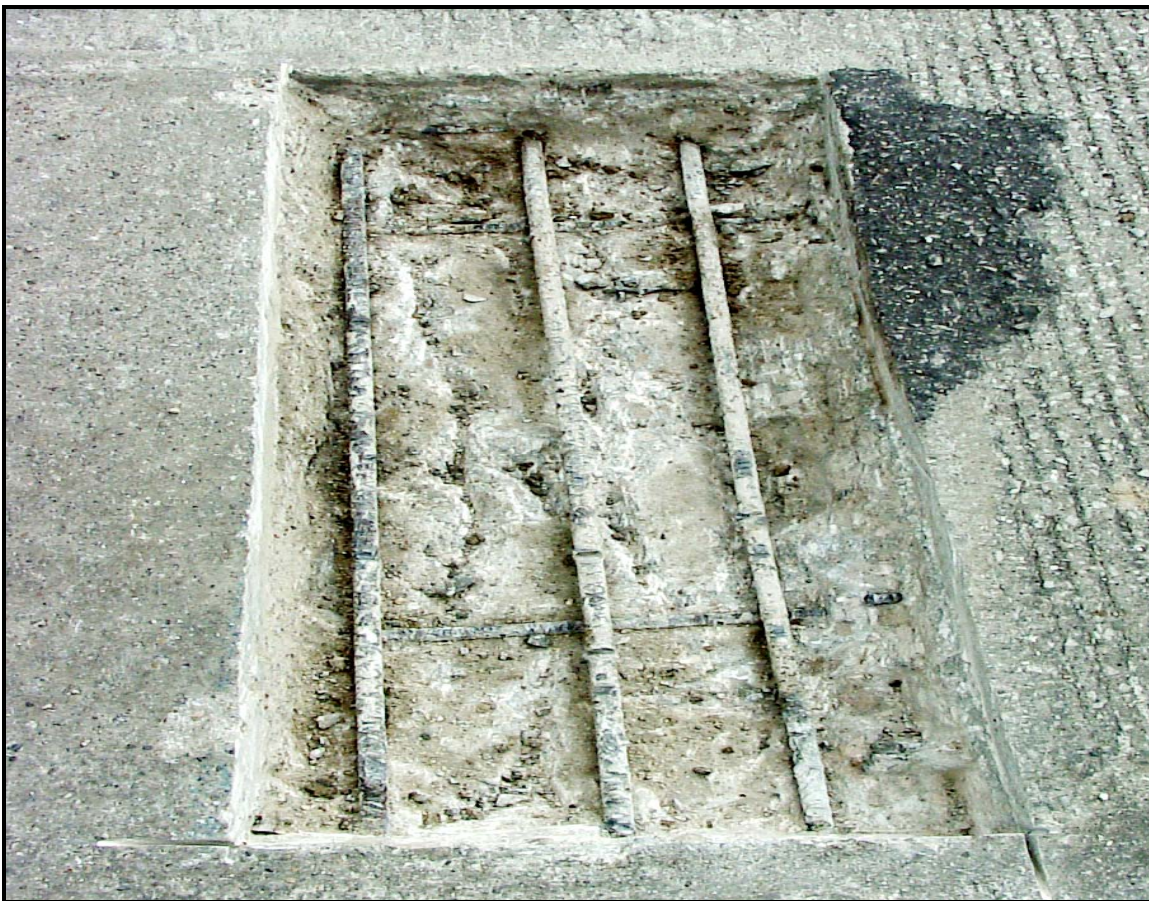


Figure 6.8: Supervisor inspecting the removal of concrete around the reinforcing steel. It should be noted that the repair material was not permitted to encapsulate the bar in this example.

The final step of surface preparation encompasses the placement of a compressible insert as a joint bond breaker, if the patch abuts a working joint or crack. Typically, styrofoam or asphalt-impregnated fiberboard are used for this purpose. However, no compressible inserts were required for any of the patches in this case study.



Figure 9: The repair patch after all the concrete surrounding the steel has been chipped away

6.4.4 Step 4: Placement of the Repair Material

The repair material should be placed as quickly as possible after preparing the patch area while the exposed concrete is clean and dry (Concrete Repair Manual, 1999). Some partial-depth patching materials may require bonding agents in order to improve

the bonding between the repair material and the substrate. When bonding agents are used, it must be applied in a thin, even coat and should cover the entire repair area including the patch walls to ensure adequate bond. In this case-study however, no bonding agents were used and the repair material was directly placed on the prepared substrate.

In recent years, rapid-hardening cementitious repair materials are being increasingly used for patch operations, as these materials minimize the out-of-service time for repairing pavements and bridge decks. Since the repair depth and volume are usually small, the rapid heat generation of the rapid-hardening materials is only a secondary concern. These materials include concretes made with Type III portland cement, concretes containing regulated-set portland cement, gypsum-based concrete, magnesium phosphate concrete, and concrete containing high alumina cement.

In this case-study, Set-45, a magnesium phosphate based rapid setting material was used. Set-45 is a one component concrete repair and anchoring material which sets in 15 minutes and will accommodate rubber-tyre traffic 45 minutes after placement (Degussa Construction Chemicals Material Data Sheet). It has a typical working time of 30 minutes and can be installed in a temperature range between 0C and 43C. Set-45 is extremely sensitive to water on the pavement, and even a very small amount of extra water in the mix severely decreases its strength (Wilson et al. 1999). It should also be noted that this cannot also be used with limestone aggregates (Smith et al., 1991).

The volume of material required for repairing a prepared patch area is often small, 0.014 m³ to 0.057 m³, and small drum or paddle-type, or jiffy mixers are used for batching (Patel et al. 1993). In the case of the INDOT field trial, a drum mixer was employed for mixing the repair material. Set-45 which comes in pre-packaged 50 lb bags

was mixed with the aggregate, which was weighed using a pre-calibrated volume method, where a bucket was marked by volume for the appropriate weight. Requisite amount of water was added based on the manufacturers' stipulations, as mentioned on the bag. Since there was only a 30 minute time-frame available between mixing the repair material, and placing and finishing operations, only 4-5 bags of Set-45 were mixed at one time in the mixer. The materials were already batched so that there was no time wasted in weighing the materials on site. Figure 6.10 shows the mixer on site.



Figure 6.10: Drum mixer used for mixing

6.4.5 Step 5: Finishing and curing operations

The mixer was conveniently located near the prescribed patch so that the mix could be placed directly into the excavated patch, as shown in Figure 6. 11. Depending on the size of the patch, the amount of material to be mixed was calculated. Ideally, the total amount of repair material used for a particular patch should be obtained by operating the mixer for a maximum of three times. Else, two mixers should be used for mixing operations. As the mixture is usually designed as self-consolidating concrete, there is no need to use a vibrator for consolidating the material. Figure 6.12 shows the partially finished patch. It should be noted that the patch is finished in parts as and when the mixed material is placed in the patch.



Figure 6.11: Convenient location for the mixer near the repair patch

Once the final batch of repair material was placed in the repair hole, the repaired patch was completely finished once again in order to remove the excess material and to ensure uniformity and homogeneity with the existing pavement surface. Figure 6.13 shows the completed patch.



Figure 6.12: An INDOT worker finishing the Freshly Placed Patch

Curing is important for partial-depth repairs as they often have large surface areas in relation to their volumes as a result of which moisture can be lost quickly (Wilson et al. 1999). Improper curing can result in shrinkage cracks that can cause the repair to fail

prematurely. Since different repair materials require different curing procedures, manufacturers' specifications must be followed strictly. The facility should not be opened to traffic should not be opened until the patch has adequately cured. In this case-study, the material was allowed to cure for an hour before it was re-opened to traffic. In this time, however, clean-up operations were performed as illustrated in Figure 6.14

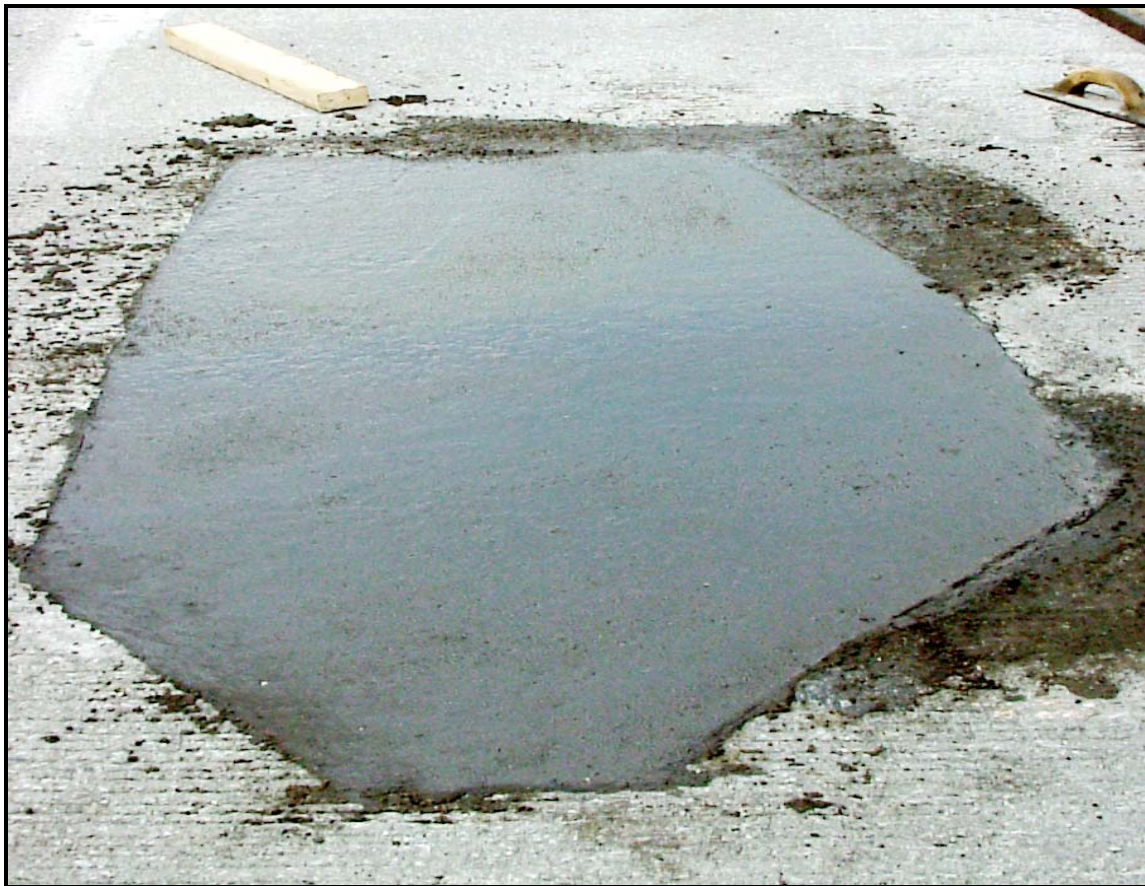


Figure 6.13: A Finished Patch



Figure 6.14: Clean-up operations during curing time

Measurements of all patches were made after the patch had sufficiently hardened in order to estimate the total volume of repair work that was accomplished within the time frame. This gives an idea about the productivity of the repair process. Figure 6.15 shows measurements being taken in order to calculate the total volume of work done on that particular day.

Quality control and inspection of the entire construction process is crucial to the success of partial-depth repair. Field experience has shown that each step in the partial-depth spall repair process requires careful supervision and inspection (Wilson et al. 1999). An inspector must continually observe the various operations to ensure that proper

procedures are being followed and adhered to. It is important that repairs are inspected periodically in order to document the field performances of different types of repair materials and techniques. This documentation should include techniques, equipment, and materials employed for removal, surface preparation, batching, placing, and curing, repair date and cost, assessment date and performance (REMR technical document, 1994).



Figure 6.15: Measurements of the repaired patch being taken

6.5 Summary

Several key factors influence the performance that can be expected from a partial-depth patch repair. These factors include the appropriateness of the repair strategy, the performance of the repair materials, the quality of removal of damaged material, the preparation of the parent material to receive the repair, and the construction, curing and inspection of the repair once it is placed. The construction steps described here have been compiled based on the experience of several agencies which have had good experience with repairing partial-depth patches and on the experiences of an INDOT crew which was selected due to their record of good performance. It should be noted however that care must be taken to follow each of these steps during the repair process and even following the detailed steps as reported in this chapter some of the patches that were observed to deteriorate approximately one year after their placement.

CHAPTER 7: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 SUMMARY

The efficient repair and replacement of concrete pavements often requires a rapid setting material that can be placed, cured, and opened to traffic in a relatively short period of time. Frequently, temporary repairs are made using materials that are later found to be incompatible with the existing pavement, structures, and environment. The objective of this research program was to evaluate the mechanical properties (strength, set time, elastic modulus, and bond strength), rate of mechanical property development, and the volumetric properties (shrinkage and restrained shrinkage cracking) of rapid setting cement-based repair materials that will be used in applications ranging from the patching for the INDOT. This report reviews the factors that should be considered in selecting a repair material (Chapter 2). It outlines the materials that were tested as well as the testing procedures that were used (Chapter 3). It illustrates how the maturity method can be used to interpret the data obtained from these tests. It provided data that would enable the performance of the materials to be simulated over a wide range of temperatures at the time of application (Chapter 4). Chapter 5 provides a detailed presentation of all of the testing results and provided a summary of the most salient features. Chapter 6 provides a summary of good repair practices that is accompanied by a short video documenting one repair that was performed by the INDOT.

7.2 CONCLUSIONS

The goal of this project was to provide the INDOT with information to fully assess and compare the performance of various rapid setting repair materials. Table 7.1 (Copied from 5.1) contains information on the initial set, final set, long term values for compressive strength, flexural strength, elastic modulus, and rate constants to describe the development of compressive strength, flexural strength, elastic modulus,. In addition, results are presented from the unrestrained shrinkage tests, restrained ring tests, and bond strength tests. Further testing is necessary to evaluate the durability of these materials.

It was observed that the repair materials investigated in this study show a wide range of properties. All of the materials tested had a long-term compressive strength of over 4000 psi, a modulus of 3,000,000 psi, and set between 10 minutes and 2 hours. Results of the bond strength tests demonstrated higher bond strengths in shear than tension. In addition, these materials showed greater variability in the tensile bond strength than they did in shear. The materials showed a wide range of unrestrained length change (as measured from the time of set) from materials that expanded to materials that shrank by as much as 800 $\mu\epsilon$ at 28 days. In addition to monitoring unrestrained length change, the restrained ring test was used to assess the cracking potential of these materials when they were restrained. While several materials exhibited expansion and no residual stress development, other materials demonstrated residual stresses that were nearly 75% of the tensile strength at 7 days. It is recommended that Table 7.1 be used for the selection of laboratory mixtures to investigate for use in the follow-up study on evaluating the field performance of joint repairs.

Table 7.1a Summary of Material Properties Tested

Material	Setting Time			Compressive Strength		Flexural Strength		Elastic Modulus		Ultrasonic Wave Speed	
	Initial Setting Time	Final Setting Time	M_o (°C*day)	S_{∞}	$C-K_t$	S_{∞}	$F-K_t$	S_{∞}	$m-K_t$	S_{∞}	$U-K_t$ (for S^2)
	minutes	minutes	°C*day	psi	psi/°C/day	psi	psi/°C/day	psi	psi/°C/day	m/s	m ² /s ² /°C/day
BASE	105	139	2.220	10060	2.5	1332	2.6	4793043	6.6	4179	12.7
DOTP	42	48	0.763	6863	10.6	812	5.2	4908046	25.6	4159	139.2
EMACO	23	33	0.521	4130	1.4	734	0.9	5607692	2.2	4414	6.6
FX	9	10	0.163	7477	5.2	768	12.6	5367522	12.9	4048	40.2
HPC	24	27	0.431	6433	13.4	530	9.1	4520364	14.3	3981	30.3
PPF	42	50	0.799	6011	1.2	645	10.9	4131793	2.1	3557	109.1
QRRR	80	89	1.422	7336	1.6	619	2.7	4272472	4.1	4081	21.7
SET45	8	9	0.147	5277	87.5	492	4.3	5244494	5.5	4319	153.5
SET45HW	38	41	0.655	5538	12.8	460	33.1	5100000	16.1	3961	116.6
SP	75	81	1.294	4237	0.1	548	0.1	3068949	0.5	3928	3.8
SSRP	13	20	0.315	7051	11.3	740	27.2	5193319	20.2	4033	138.5
THOROC	32	35	0.561	5070	17.7	430	12.7	4438566	11.0	3971	103.9

Table 7.1b Summary of Material Properties Tested

Material	Activation Energy	Temperature	Volume Stability			Bond			
	E_A	Maximum Temperature	28 Day Autogenous Shrinkage	28 Day Total Shrinkage	Cracking Potential at 7 Days	Shear Bond Strength (Smooth)	Shear Bond Strength (Rough)	Tensile Bond Strength (Smooth)	Tensile Bond Strength (Rough)
	J/mol	°C	µε	µε	~	psi	psi	psi	psi
BASE	55816	31.5	-390	-780	0.20	542	645	216	347
DOTP	64781	50.3	-270	-360	0.16	392	528	57	255
EMACO	6545	37.4	-360	-450	0.60	657	643	241	170
FX	22312	39.8	-318	-245	0.14	501	566	163	329
HPC	27685	39.7	-159	-277	0.75	705	695	212	318
PPF	28270	51.0	-302	-507	0.38	435	663	166	336
QRRR	18163	36.3	127	-10	~	394	476	156	226
SET45	31099	69.3	630	690	~	343	370	163	166
SET45HW	63495	59.3	70	-70	~	218	307	74	265
SP	10271	33.0	110	10	~	347	374	297	81
SSRP	43079	50.4	-130	-220	~	337	456	35	357
THOROC	5129	49.9	-120	-370	0.70	396	474	233	343

Materials like BASE should be discouraged when they are in contact with reinforcement due the chlorides that are used in these materials which could lead to corrosion. EMACO, PPF, QRRR, and SP show a relatively slower strength gain than the other materials and may not enable the most rapid opening of the pavement to traffic. As such it appears that FX, SET45, SSRP should

be considered for the next phase of the study with possible consideration of HPC and THOROC if the potential for residual stress development due to restrained shrinkage can be reduced.

7.3 Recommendations

This report has investigated the compressive strength, flexural strength, elastic modulus, set time, bond, strength gain, bond strength, strength and restrained cracking potential. Table 5.1 provides a concise summary of different commercially available rapid setting patch materials. It should be noted that while this table can be used to obtain information about the mechanical and volume properties, tests for durability were not performed on these materials

- It is recommended that the INDOT follow up this study with durability tests and field trials of promising materials. The laboratory tests would primarily focus on the freeze-thaw durability and the potential for corrosion (where reinforcing steel may be present). For the field trials these materials may be used in several concrete pavements that have been built in the state of Indiana show deterioration at the longitudinal and transverse joints. The performance of these field installations should be monitored.

It became evident from the survey that different districts have differing experiences regarding which repair practices are most successful. A large portion of the success of any repair is based on the quality of the repair material, the suitability of the repair material for the application, and the quality of the preparation of the parent concrete for the repair as well as the attention to detail during the repair process.

- It is recommended that the INDOT develops a summary of repair practices. It is suggested that this summary may be used as a part of a one-day workshop with repair crews to discuss their experience with repair and to train them on best repair practices. It is recommended that the INDOT develop a training module that expands on the small video that was made as a part of this project indicating the impact that construction can have on the performance of the repair.

The current ASTM testing procedures do not enable the very early age shrinkage to be measured. Similarly the recently standardized restrained ring test does not measure the effects of expansion.

- It is recommended that new testing procedures be developed and standardized to assess the volumetric shrinkage and restrained stress development.

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APPENDIX B

Question 1: Please fill out the table as applicable

	Materials used for each type of repair	Procedures used for each type of repair	Surface preparation procedures
Quick Patching			
Patching			
Stitching			
Potholes			
Full Depth Repair			
Bridge Deck Repair			

Question 2: What types of quality control testing do you typically use?

Question 3: Are there any temperature/moisture restrictions on when you can perform repairs?

Question 4: How do you determine when the repair can be opened to traffic?...cast-in-place specimens, maturity methods, etc.?

Question 5: Are there any special procedures you use for curing the concrete?...sealing the concrete?

Question 6: Do you typically do repairs 'in-house', or contract out?

Question 7: Could you please indicate whether or not you have used the following repair materials and what your experience was with them. The first 8 are from the INDOT approved list. Please note that the list of materials is continued on the other side of this page.

REPAIR MATERIAL (Manufacturer)	Have Used?	Experience
MONO-PATCH HOT WEATHER (Bindan Corp.)		
MONO-PATCH NORMAL TEMP (Bindan Corp.)		
THOROC 10-61 HOT WEATHER (ChemRex, Inc.)		
THOROC 10-60 NORMAL TEMP (ChemRex, Inc.)		
SET 45 HOT WEATHER (Master Builders Inc.)		
SET 45 NOMRAL TEMP (Master Builders Inc.)		
DURACAL AG HOT WEATHER (U.S. Gypsum Co.)		
DURACAL NORMAL TEMP (U.S. Gypsum Co.)		
SR 2000 CONCRETE REPAIR (Southeast Resins, Inc.)		
BONSAL RAPID PATCH – VR (W.R. Bonsal Co.)		
BONSAL FAST SET CEMENT MIX (W.R. Bonsal Co.)		
FAST PATCH 928 (The Burke Company)		
PAVE PATCH 3000 (Conspec Marketing & Mfg. Co.)		
FIVE STAR HIGHWAY PATCH (Five Star Products)		
TECTONITE (CFB, Inc.)		
SPEED CRETE 2028 (Tamms Industries)		
SPEED CRETE GREEN LINE (Tamms Industries)		
HIGH PERFORMANCE CEMENT (US Concrete Products)		

PRE-KRETE FS-16 (Andee Boiler & Welding Company)		
CONSPEC SPECIAL PATCH (Conspec Marketing & Mfg. Co.)		
POLY PATCH (Symons Corporation)		
SPEED CRETE RED LINE (Tamms Industries)		
MAGNA 100 (American Stone-Mix, Inc.)		
DAY-CHEM PERMA PATCH (Dayton Superior Corporation)		
FX-928 RAPID SETTING MORTAR (Fox Industries, Inc.)		
FX-930 RAPID SETTING CEMENT (Fox Industries, Inc.)		
SYMONS DOT PATCH (Symons Corporation)		
QUIKRETE RAPID ROAD REPAIR (The Quikrete Companies)		
SEALTIGHT FUTURA 15 (W.R. Meadows)		
CHEMSPEED 55 (Chemmasters, Inc.)		
CHEMSPEED 65 (Chemmasters, Inc.)		
EUCO-SPEED MP (Euclid Chemical Co.)		
SET INSTANT (Master Builders Inc.)		
EMACO T415 (Master Builders Inc.)		
SIKASET ROADWAY PATCH (SIKA Corporation)		